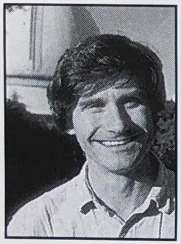

Professor Alex Filippenko is Professor of Astronomy at the University of California at Berkeley. He holds a Ph.D. in astronomy from California Institute of Technology. The most widely cited researcher in Astronomy, he has published over 430 papers. *Science* magazine credited his research team with the "Science Breakthrough of 1998" for research on exploding stars (supernovae). He was voted "Best Professor" by UC Berkeley students in 1995, 2001, 2003, and 2004.

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Science & Mathematics

Understanding the Universe:

What's New in Astronomy, 2003

Taught by: Professor Alex Filippenko,
University of California at Berkeley

Part 1

Course Guidebook

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Alex Filippenko, Ph.D.

Professor of Astronomy, University of California, Berkeley

Alex Filippenko received his bachelor's degree in physics (1979) from the University of California, Santa Barbara, and his doctorate in astronomy (1984) from the California Institute of Technology. He subsequently became a Miller Postdoctoral Fellow for Basic Research in Science at the University of California, Berkeley. In 1986, he joined the faculty at UC Berkeley, where he has remained through the present time. A member of the International Astronomical Union, Filippenko has served as President of the Astronomical Society of the Pacific and as Councilor of the American Astronomical Society.

An observational astronomer who makes frequent use of the Hubble Space Telescope and the Keck 10-meter telescopes, Filippenko's primary areas of research are exploding stars (supernovae), active galaxies, black holes, and cosmology. He and his collaborators recognized a new class of exploding star, obtained some of the best evidence for the existence of small black holes in our Milky Way galaxy, and found that other galaxies commonly show vigorous activity in their centers that suggests the presence of supermassive black holes. His robotic telescope at Lick Observatory in California is the world's most successful search engine for nearby supernovae, having discovered more than 300 of them in the past few years. Filippenko also made major contributions to the discovery that the expansion rate of the Universe is speeding up with time (the *accelerating Universe*), driven by a mysterious form of dark energy—the top "Science Breakthrough of 1998," according to the editors of *Science* magazine.

Filippenko's research accomplishments, documented in more than 430 published papers, have been recognized with several major awards, including the Newton Lacy Pierce Prize of the American Astronomical Society (1992) and the Robert M. Petrie Prize of the Canadian Astronomical Society (1997). A Fellow of the California Academy of Sciences, Filippenko has also been a Guggenheim Foundation Fellow (2001), a Phi Beta Kappa Visiting Scholar (2002), and a distinguished visiting lecturer at numerous colleges and universities, including the Spitzer Lecturer at Princeton University.

Filippenko has won the coveted Distinguished Teaching Award (1991) and the Donald S. Noyce Prize for Excellence in Undergraduate Teaching in the Physical Sciences (1991), each of which is generally given at most once per career. In 1995, 2001, and 2003, he was voted the "Best Professor" on campus in student polls. Also, in 2002, he won the UC Berkeley Distinguished Research Mentoring of Undergraduates Award. He has delivered hundreds of public lectures on astronomy and has played a prominent role in science newscasts and television documentaries, such as "Mysteries of Deep Space," "Stephen Hawking's Universe," and Nova's "Runaway Universe." With Jay M. Pasachoff, Filippenko coauthored an introductory astronomy textbook, *The*

Cosmos: Astronomy in the New Millennium (2001; 2004, 2nd ed.), which in 2001, won the Texty Excellence Award of the Text and Academic Authors Association for the best new textbook in the physical sciences. In 1998, Filippenko produced a 40-lecture introductory astronomy video course with The Teaching Company, to which the present course is an update.

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Music for this course
written and performed by Matt Venuti and The Venusians: venusians.com

Understanding the Universe: What's New in Astronomy, 2003

Scope:

This visually rich course is designed to provide a nontechnical update to Professor Alex Filippenko's first astronomy course for The Teaching Company, *Understanding the Universe: An Introduction to Astronomy*, which was produced in 1998. Much has happened in the world of astronomy during the past five years, and the primary objective of this course is to discuss some of the more exciting and important advances. Although this course is largely self-contained, you will certainly find it beneficial to view the original introductory course to familiarize yourself with astronomical concepts and to gain sufficient background information that will allow you to more fully understand and enjoy this new set of lectures.

In Part I, the first two lectures are on simple daytime and nighttime observations that you can make to better appreciate the sky and what it contains. Topics include sunspots, partial solar eclipses, the setting Sun and the green flash, Buddha's rays, planets, the Milky Way, constellations, observations with binoculars and small telescopes, northern lights, and more. Lecture Three is devoted to recent advances in our Solar System made with satellites and sophisticated ground-based techniques. One of the most important conclusions, from the discovery of numerous objects near and beyond Pluto's orbit, is that Pluto is not a true planet but, rather, just the largest known member of the Kuiper Belt of icy minor planets. In Lecture Four, we discuss the rapidly moving field of *extrasolar planets*—planets that orbit stars other than the Sun. More than 100 such objects are now known, and we can begin to draw interesting statistical conclusions about them. The formation and evolution of stars is the subject of Lecture Five, a highlight of which is the resolution of the long-standing *solar neutrino problem* and the resulting conclusion that neutrinos have nonzero mass. Moreover, the discovery of large numbers of brown dwarfs, which bridge the gap between giant planets and normal stars, has contributed to an improved appreciation of their true nature.

Lecture Six describes the catastrophic explosions of certain types of stars at the ends of their lives, creating and ejecting into the cosmos the elements of which humans are made. With the discovery and detailed study of many supernovae during the past few years, we now have a much better understanding of stellar explosions and their remnants. Lecture Seven concentrates on the enigmatic *gamma-ray bursts*, whose distances and physical properties were extremely uncertain until recently. We now know that they generally reside in very distant galaxies and, in most cases, are associated with massive stars that collapse or merge to form black holes, high-speed jets of particles, and colossal explosions. Lecture Eight gives strong observational evidence for the existence of black holes, both the stellar-mass variety in binary systems and the supermassive objects in the centers of galaxies. Black holes really do exist! Recently, black holes that are intermediate in mass between the two major known classes appear to have been found.

Lecture Nine, the first lecture of Part II, is devoted to a brief introduction to Einstein's special and general theories of relativity, because their consequences are so abundant among astronomical phenomena. Past and future tests of these theories are described, most notably the search for gravity waves. Cosmology and the expansion of the Universe are the subjects of Lecture Ten. The expansion age of the Universe, 13.7 billion years, has recently been determined with high accuracy, and it slightly exceeds the ages of the oldest known stars; thus, the persistent *age crisis* finally appears to have been resolved. Lecture Eleven discusses the birth and evolution of galaxies, which can be investigated by looking back in time at progressively more distant galaxies. We also consider the *cosmic microwave background radiation*, which predates the light from the first generation of stars and is actually the afterglow of the Big Bang.

The 1998 discovery that the expansion of the Universe is speeding up with time was new and quite uncertain at the time of the 1998 astronomy course, but the evidence is now much better, as discussed in Lecture Twelve. Studies of distant supernovae continue to suggest that there is a dark, repulsive energy pervading space, causing galaxies to recede from each other ever faster. As described in Lecture Thirteen, independent confirmation of this revolutionary conclusion was recently provided by satellite measurements, which showed that the Universe is geometrically flat on large scales and, therefore, must have a substantially higher density than can be explained with visible and dark matter alone. In addition, most of the dark matter must consist of unknown particles that differ from ordinary matter. Given that almost three-quarters of the energy content of the Universe is repulsive *dark energy*, it behooves us to understand its nature; this is the subject of Lecture Fourteen. One possibility is that quantum fluctuations (virtual particles) in the vacuum are the origin of dark energy, but there are problems with this hypothesis. A complete understanding of dark energy probably won't be possible until we have a successful *theory of everything*, unifying quantum physics with general relativity. As discussed in Lecture Fifteen, the most extensive work in this area has been done on *superstring theories*, which postulate that every elementary particle is a different mode of vibration of a tiny energy packet known as a *string*. A strange attribute of such theories is that the Universe contains many hidden dimensions, and physicists are now trying to find experimental evidence for them. In Lecture Sixteen, the course ends by summarizing the way in which an early epoch of exponential expansion can resolve the problems with the standard Big Bang theory. This leads to the notion of multiple universes, possibly having a range of properties—and, naturally, we live in one of the hospitable universes!

Lecture One

From Dawn to Dusk

Scope: This course focuses on astronomical discoveries made since 1998, when The Teaching Company's *Understanding the Universe: An Introduction to Astronomy* was produced. A broad selection of topics is included. Some subjects for which there was inadequate time in the first course are also covered to provide an even more thorough overview of modern astronomy. We begin with a discussion and physical explanation of some of the interesting celestial and atmospheric phenomena visible during the day and near sunrise or sunset to whet the appetites of stargazers waiting for nightfall. These include sunspots, partial solar eclipses, rainbows, solar halos, *sun dogs*, pillars, beautiful sunset colors, mirages, the *green flash*, *Buddha's rays*, and the Earth's shadow on the atmosphere. We will also learn safe methods for viewing the Sun.

Outline

I. In this lecture, we will discuss a variety of celestial and atmospheric phenomena visible during the day, starting with sunspots, which are cooler spots on the Sun's "surface," or *photosphere*.

  A. You can observe the Sun safely by viewing it through Shade #14 welder's glass, which can be purchased at welding supply stores.

  B. A telescope provides a magnified view; many more spots should be visible.

    1. If you look directly through the telescope, you must first attach a proper filter to the top end of the telescope to decrease the amount of light being collected.

    2. Eyepieces are sometimes sold with small filters attached to them, but you should not use these because they can heat up and crack, and the concentrated sunlight can severely damage your eyes.

  C. A safer method that allows many people to view the Sun simultaneously is to project its image onto a white screen. In this case, a filter should not be placed on the telescope. However, the image will be relatively faint if the hole is small.

  D. A convenient gadget that allows you to also trace the outlines of sunspots on a sheet of paper is a *sunspotter*, which is commercially available. Doing this over the course of a week or more allows you to track the rotation of the Sun by monitoring the sunspots.

II. Partial solar eclipses are fun to watch, though they are fairly rare at any given location (occurring perhaps once every few years).

A. You can view these through Shade #14 welder's glass.

B. You can also project the image of the Sun onto a blank screen by using a pinhole camera made out of cardboard.

C. You can project an image onto a screen through a telescope or a pair of binoculars.

D. The totally eclipsed Sun can be viewed directly with the eyes or through binoculars or a telescope with no filter. Total solar eclipses are rare.

III. Rainbows are beautiful and much more frequent than solar eclipses.

A. When sunlight enters a spherical raindrop (they are, indeed, almost always spherical), the light is bent (*refracted*) by different amounts, depending on color. Violet light is refracted the most, and red light, the least.

B. The light then bounces (*reflects*) off the back side of the raindrop and exits toward the front of the drop, but at an angle relative to the incoming light ray. This light forms the *primary rainbow*.

1. The angle is slightly different for each color, but it is roughly 42 degrees from the direction in the sky directly opposite the Sun. Thus, the radius of the primary rainbow is about 42 degrees.

a. If the Sun is close to the horizon, you will see nearly a full semicircle.

b. If the Sun is high, you will see a smaller arc close to the ground.

c. A complete rainbow can only be seen if you are looking down into a canyon, observing from an airplane, or viewing from a similar vantage point.

2. The inner part of the primary rainbow is blue, and the outer part is red.

3. The light that enters your eyes from the red part of a rainbow comes from a different set of drops than the light from the blue part of the rainbow.

4. Every drop along a given color light ray bends that same color to your eye.

5. The very drop that sends blue to you sends some other color to an observer elsewhere.

6. If you change locations, the rainbow will be formed from a different set of raindrops. Thus, the rainbow moves with you.

C. Light that bounces twice within the raindrop exits at a completely different angle and forms a fainter secondary rainbow, in contrast to the primary rainbow formed by light that has experienced only one internal reflection.

1. The colors of the secondary rainbow are reversed: The inner part is red; the outer, blue.

2. The secondary rainbow has a radius of about 51 degrees.

D. Why do the rays bunch up at a particular angle, allowing one color to not mix much with other colors?

1. Light is sent in many directions, depending on where it enters the drop of water.

2. However, there is an area where the rays can enter the drop and exit at nearly the same angle.

3. Because the exit angle changes only slowly as a function of the entrance point, the rays bunch up at that angle.

E. Next to the blue light of the primary rainbow, you can sometimes see faint bands, called *supernumerary bows*. These are produced by light waves interfering with each other.

F. Sometimes, especially near the time of the full moon, a lunar rainbow, or *moonbow*, can be seen at night.

IV. The *sun halo*, a ring around the Sun having a radius of about 22 degrees (rather than 42 degrees), is related to rainbows.

A. It is formed when sunlight goes through (and is bent by) ice crystals in the atmosphere, shaped like hexagonal prisms. High cirrus clouds consist of such crystals, randomly oriented.

B. At a point on either side of the Sun, at the same altitude as the Sun above the horizon, the halo can be especially bright, forming *sun dogs* (or *mock suns*). They are actually at a slightly larger radius from the Sun than the halo.

1. Sun dogs are often seen alone, when the rest of the solar halo is invisible; they are brighter than the halo.

2. They are produced when the ice crystals tend to be oriented with their hexagonal flat faces parallel to the ground.

C. A similar, but fainter, 22-degree halo can be seen at night around the Moon, especially when it is full.

D. Another phenomenon is the *corona*—a diffuse glow of light immediately around the Sun or Moon, having a much smaller radius than the halo.

1. It is produced by *diffraction*, the bending of light around droplets of water.

2. The effect can also be seen when looking at headlights through fog.

3. If you are on a mountaintop and cast a shadow on valley fog, a corona is sometimes visible around your shadow.

E. Hexagonal ice crystals can also produce a pillar of light above the Sun, best visible just after sunset.

    1. The ice crystals reflect light in your direction.
    2. This is somewhat similar to the pillar of light formed below the Sun or Moon by surface ripples on a lake or ocean.

V. The setting Sun generally looks orange or even red.

- **A.** Blue and green light is selectively absorbed by dust in the atmosphere, and it is preferentially scattered away by air molecules. The preferential scattering of blue light produces the blue daytime sky.
- **B.** Closer to the horizon, sunlight goes through a longer path and experiences more scattering and absorption; thus, the Sun's disk looks progressively redder.
- **C.** The Sun has actually already set when it appears just above the horizon. The angular offset is about one solar diameter.
    - **1.** The Earth's atmosphere refracts sunlight, so that it follows a curved path before entering our eyes.
    - **2.** However, our eyes do not know that light followed a curved path; they just see the direction from which the light entered.
    - **3.** Extrapolating the rays back into space, they appear to come from a point higher up in the sky than the Sun's actual (physical) position. The Sun, therefore, looks as if it is still above the horizon.
    - **4.** This effect happens at both sunset and sunrise, thereby extending the length of the day by a few minutes at each end.

VI. Right at the moment of sunset or sunrise, an interesting effect known as the *green flash* can sometimes be seen if skies are clear and free of dust and if you are observing from a location with a good true horizon (unobstructed by mountains or buildings).

- **A.** The final tiny portion of the Sun appears green just before it sets. This typically lasts for only a second or two.
- **B.** The explanation is closely related to the fact that the Sun still appears above the horizon for a few minutes after it has physically set.
    - **1.** The atmosphere refracts optical light that has short wavelengths more than long ones. Thus, violet light is bent the most, followed by blue, green, yellow, orange, and red.
    - **2.** Projected back onto the sky, the Sun seems to consist of several mostly overlapping disks of different colors: Violet is highest, and red is lowest.
    - **3.** But violet and blue light are heavily scattered by molecules in the atmosphere and absorbed by dust.
        - **a.** Thus, even under excellent conditions (no dust or smog in the atmosphere), the shortest wavelength to reach our eyes is green light.
        - **b.** Usually, even the green light is diminished to such an extent that only yellow, orange, and red remain.

    - **4.** The red disk sets first, followed by the orange disk, then the yellow disk.
        - **a.** The green disk is the last to set, but because it overlaps the other disks so much, in practice, only the very top sliver is visible just before it sets.
        - **b.** This means that the last light we see from the setting Sun can be green—in part explaining the green flash.
    - **5.** However, this textbook explanation for the green flash cannot be the full story, because it does not produce a sufficiently pronounced effect. One needs to also have a mirage of the Sun to detach the green part of the Sun from the rest of the disk and to prolong the phenomenon.
- **C.** Mirages generally form in two main ways.
    - **1.** An *inferior mirage* occurs when cool, dense air is above hot, less dense air, as is often true over a hot asphalt road.
        - **a.** Incoming light from the sky is bent slightly upward, reaching the eye at a somewhat more horizontal angle than would otherwise have been the case.
        - **b.** This creates an image of the sky close to the ground—the familiar "lake in the desert" effect
    - **2.** A *superior mirage* occurs when cold, dense air is below hot, less dense air, as is often true over a cold body of water.
        - **a.** Incoming light from the sky is bent downward, reaching the eye at a somewhat steeper angle than would otherwise be the case.
        - **b.** This makes the light appear to come from a higher altitude above the horizon.
        - **c.** The effect is strongest from the lowest points, which then appear higher than points that are physically higher.
        - **d.** This produces an inverted image of the object. Ships sailing on northern oceans, for example, can appear inverted for this reason.
- **D.** The green flash is produced by the classic textbook explanation plus appropriate mirages.
    - **1.** Usually, even the green light is too faint to see because of absorption in Earth's atmosphere, so the effect is rarely seen.
    - **2.** When looking for a green flash, if the Sun is orange or red, your chances are slim, because of material obscuring the short wavelengths.
    - **3.** Favorable conditions are signaled by a yellowish-white setting Sun.
        - **a.** In any case, a clear, true horizon is generally a prerequisite to seeing a green flash.
        - **b.** Mountains and other obstructions cause the Sun to appear to set when it is too high; thus, the refraction isn't as large.

4. Sunrises are sometimes better than sunsets for seeing the green flash, because dust in the air has had a chance to settle out during the night.
    a. Also, before sunrise, your eyes have not been partially blinded by the Sun's light; they are more sensitive.
    b. On an especially clear morning, a green flash can (rarely) appear bluish.

E. When you look for the green flash, be sure to take proper care of your eyes!

1. To monitor the progress of the setting Sun, briefly glance at it occasionally, and start looking at it continuously perhaps 10 seconds before it fully sets.
2. This procedure will also make your eyes more sensitive to the true green flash.
3. Staring at a red setting Sun will make you more vulnerable to a physiological effect—the green afterglow perceived by your brain that is the complement of red.

VII. *Buddha's rays* or *crepuscular rays* form when sunlight goes through gaps in clouds and hits the atmosphere, especially near sunrise or sunset. The air is darker in the cloud shadows.

A. The rays appear to diverge from the Sun but are actually nearly parallel.

B. Although the rays are brightest in the general direction of the Sun, they can sometimes be seen in the anti-solar direction, as well.

VIII. Shortly after sunset or before sunrise, one can see the Earth's shadow cast on the atmosphere.

A. This appears as a dark blue horizontal band below the brighter air.

B. The setting Sun is still visible from the perspective of the higher, more brightly lit atmosphere. The Sun has already set, however, as seen from lower parts of the atmosphere.

C. As the Sun gets lower and lower below the horizon, the dark part of the atmosphere climbs progressively higher, until essentially all of the visible atmosphere is in the Earth's shadow and there is no longer a clear demarcation.

IX. When the Moon is close to the horizon, it can appear very large. A similar phenomenon occurs near sunset or sunrise if there is fog or dust in the air and it is safe to look very briefly at the Sun.

A. This is just an illusion; it is easier to compare the Moon's or Sun's angular size with that of known objects (distant trees, buildings, and so on) when it is rising or setting.

B. The illusion persists even when the Moon or Sun rises over the ocean or a large lake, probably because our brains still remember how big objects appear near the horizon.

C. The Moon actually has a slightly *smaller* diameter when near the horizon, because we view it from a distance of one Earth radius farther than when it is almost overhead.

Essential Reading:

Lynch and Livingston, *Color and Light in Nature*.

Minnaert, *Light and Color in the Outdoors*.

Young, http://mintaka.sdsu.edu/GF (green flash, mirages, and so on).

Supplementary Reading:

Parviainen, http://www.polarimage.fi (green flash, mirages, and so on).

Pasachoff and Filippenko, *The Cosmos: Astronomy in the New Millennium*, 2nd ed.

Questions to Consider:

1. The image produced by a pinhole camera is inverted. Similarly, the lens of your eye produces an inverted image on the retina. Why, then, do you think we see people and other objects "right side up"?
2. How could you determine the approximate location of raindrops that produce a rainbow? (Think about viewing the rainbow against a backdrop of objects that are different distances from you.)

Lecture Two

Exploring the Night Sky

Scope: Many celestial phenomena can be enjoyed with the naked eye or binoculars. This lecture describes and explains the twinkling of stars and the relative non-twinkling of planets; the gradual motion of planets (generally from west to east) among the stars; artificial satellites, such as the International Space Station and the Iridium network; zodiacal light; comets; lunar eclipses; meteors ("shooting stars"); and the rotation of the night sky. Also discussed are a few of the main constellations, the Milky Way, and famous celestial objects, such as the Orion nebula and the Andromeda galaxy, which can be viewed with binoculars. Through a small telescope, one can get glorious views of the Moon and some planets, reproducing observations first made by Galileo. A few of the best celestial objects beyond the Solar System that can be view with a small telescope are also shown. The lecture ends with examples of *auroras*, beautiful displays of light produced by energetic particles from the Sun interacting with Earth's atmosphere.

Outline

I. Now that the Sun has set and twilight is over, it's time to start enjoying the night sky! The first phenomenon we explore is the band of light known as the Milky Way.

- **A.** To see it really well, you must be far from city lights. It will appear as a faint band of light stretching across the sky.
- **B.** It consists of countless faint stars and clouds of gas along the plane of our Milky Way galaxy, which is rather flat, like a pancake.
  - **1.** When you look along the plane, you see myriad stars.
  - **2.** When you look away from the plane, there are relatively few stars and the sky appears darker.
  - **3.** The band of light forms a full circle around you, because stars in the plane of our galaxy surround the Sun. However, at most, half of the band is visible at any given time, because the other half is below the horizon.

II. In a clear, dark sky you can also see the zodiacal light, especially during the few hours after evening twilight and the few hours before morning twilight.

- **A.** It is a conical glow that starts from the western horizon (after evening twilight has ended) or from the eastern horizon (before morning twilight begins), stretching upward in the sky.
- **B.** It consists of sunlight scattered by dust and gas in the plane of the Solar System. The scattering is most efficient in the forward direction; thus, the zodiacal light is brightest in directions closest to the Sun.

- **C.** Because the plane of the Solar System forms its steepest angle relative to your horizon during February and March in the evening and during October and November in the morning, these are generally the best months for viewing the zodiacal light.

III. While looking at the night sky, you might see artificial satellites, such as the International Space Station, moving among the stars. They shine because of reflected sunlight.

- **A.** Occasionally, extremely bright but short-lived flashes of light can be seen from Iridium satellites.
  - **1.** There is a network of about 70 satellites orbiting the Earth, but they are no longer used for telecommunications.
  - **2.** The flashes occur when one of their highly reflective solar panels diverts sunlight directly toward us.
- **B.** Information on when and where to see satellites, including Iridium flashes, can be found on the web page www.heavens-above.com for your particular latitude and longitude.

IV. Planets can be fun to monitor in the night sky.

- **A.** When not projected too close to the Sun, Venus is especially prominent, alternating between the evening and morning skies. It can be the brightest object in the nighttime sky, except for the Moon.
- **B.** When Venus is close to the crescent Moon, the pair is striking, and it is frequently noticed. Observatories tend to get many calls about UFOs at those times. (Of all objects, Venus is most frequently interpreted as a UFO.)
- **C.** At a given altitude above the horizon, a planet usually twinkles less than a star and, hence, can be distinguished from a star.
  - **1.** Stars twinkle because the turbulent atmosphere bends (refracts) their light in slightly different directions from one moment to another.
  - **2.** Planets, though intrinsically smaller than stars, are so much closer that, through a telescope, they appear as disks of light, rather than as points, like stars. So many points in the disk are twinkling independently that they tend to average out, resulting in a steadier beam.
- **D.** Planets slowly wander among the stars, generally from west to east. Indeed, *planet* means "wanderer" in Greek.
  - **1.** During a given night, stars and planets rise in the east and set in the west, but this is just a reflection of the Earth's daily rotation about its axis.
  - **2.** If you watch a planet from night to night, however, you will see it slowly moving among the stars, setting slightly later than a given star on successive nights.

    3. The motions are quite subtle but can most easily be seen when several bright planets are roughly in the same direction in the sky.
    4. Their positions relative to one another change from night to night, because they move among the stars at different rates.

V. Occasionally, you may be lucky enough to see something really special.

  A. For example, a bright comet is an awe-inspiring sight to behold.
    1. A comet is a "dirty snowball" from the outer reaches of the Solar System whose ices evaporate as it approaches the Sun.
    2. The resulting gas is pushed away from the snowball by the Sun's radiation. The gas then reflects sunlight, forming the apparent "tail."
    3. There were bright comets in 1996 (Comet Hyakutake) and 1997 (Comet Hale-Bopp), but we don't know when the next bright comet will appear.

  B. Another beautiful spectacle is a total lunar eclipse, when the Moon enters the Earth's shadow.
    1. During the first partial phases, which can last over an hour, more and more of the Moon is immersed in the Earth's shadow.
    2. Totality itself can last about an hour but is often shorter.
      a. The Moon is not totally dark during totality, because some sunlight is bent around the Earth by the atmosphere and subsequently reaches the Moon.
      b. The color of the Moon during totality is typically orange or red, for the same reason that sunsets are orange/red: The blues and greens are selectively absorbed and scattered by Earth's atmosphere.
    3. After totality ends, progressively more of the Moon comes out of the Earth's shadow, taking about an hour to exit.

VI. It is fun to take long-exposure photographs of the sky with a single-lens reflex (SLR) camera attached to a tripod.

  A. Set the focus to infinity, make the lens opening wide (that is, set it to a low *f*-number), disable the flash unit, attach a cable release to the camera, and point the camera in the desired direction. Make sure that the camera is set properly for long exposures (normally the "B" or "bulb" setting).

  B. Then, start the exposure with the cable release. End it after a few minutes. (The darker the sky, the longer you can expose without fogging the film.)

  C. When the film is developed, you will see star trails whose length is proportional both to the angular distance from the celestial pole and to the duration of the exposure.

  D. If you are lucky, you might catch a meteor in your photograph.

    1. Such "shooting stars" are actually small pebbles (like grains of sand) burning up in the Earth's atmosphere because of friction.
    2. You increase your odds by exposing during a meteor shower.
    3. The debris from a disintegrating (or long dead) comet passes through the atmosphere.
    4. Because all the debris is coming from the same direction, along parallel paths, it seems to diverge from a single point known as the *radiant*—just as parallel railroad tracks diverge from the distant *vanishing point*.

  E. A meteor shower is named after the constellation in which the radiant is located (for example, Leo for the Leonids; Perseus for the Perseids).

VII. Some of the main constellations in the sky are easily recognized.

  A. Orion, the great hunter, is a prominent winter constellation. The belt consists of three bright, closely spaced stars. Extending the belt to the left, you reach Sirius, the brightest star in the sky, part of the constellation Canis Major (the "Great Dog").

  B. The Big Dipper is also well known.
    1. Actually, it is only part of a constellation, Ursa Major (the "Great Bear").
    2. The two end stars in the bowl point roughly to Polaris (the "North Star"), which is famous but not one of the brightest stars in the sky.

  C. Polaris is the final star at the end of the handle of the Little Dipper (the "Small Bear"), which is significantly harder to recognize than the Big Dipper.

  D. A star chart for the appropriate month of the year should be used to assist you in locating constellations. People sometimes find these to be confusing, because east is to the left and west is to the right, not as they are on a normal map. But this orientation makes sense if the chart is used in the correct manner.
    1. If you are facing south, align the chart so that its southern part points south when you hold the chart above your head. East and west will be in the correct directions, and the stars in the sky should match those on the chart.
    2. Similarly, if you are facing north, align the northern part of the chart so that it faces north when you hold the chart above your head.

VIII. Constellations and star patterns are used to find famous celestial objects that can be viewed with binoculars.

  A. A bright triangle of stars in the summer months (the *Summer Triangle*) consists of Vega, Deneb, and Altair. Going from Vega through Deneb and beyond, one reaches Pegasus and Andromeda.

1. A fuzzy patch of light in Andromeda is M31, the Andromeda galaxy, which is 2.4 million light years away but can be seen with the naked eye.
2. This spiral galaxy is also near the easily recognized "W" of Cassiopeia.

B. Below Orion's distinctive belt, in the sword, is the Orion nebula, a giant cloud of gas from which stars are being born.

C. Extending Orion's belt to the right, you reach Taurus (the "Bull") and its bright star Aldebaran, then the Pleiades ("Seven Sisters").

D. Cruising through the Milky Way with binoculars is also fun. The star clusters and nebulae are especially prominent in Scorpius and Sagittarius, toward the central regions of the Milky Way galaxy.

E. The Moon is a fine sight through binoculars, especially during the crescent and quarter phases, when shadows are prominent on its surface.

IX. Through a small telescope, you can see these same objects and many others.

A. The Moon and the brightest planets are easy to look at.

1. Sometimes, you can even watch the Moon *occult*, or "pass across," a planet.
2. Saturn's rings are quite face-on throughout 2003 and 2004; afterward, they will gradually become more edge-on.
3. Jupiter's main bands can be seen, as can Jupiter's four bright moons. Monitoring the motions of these moons, you can reproduce the famous observations made by Galileo.
4. You can also monitor the phases of Venus. The complete set of phases of Venus was the fatal blow to the geocentric (Ptolemaic) model for the Solar System.

B. A beautiful globular star cluster, M13, can be found in Hercules. It consists of several hundred thousand very old stars.

C. Nearby, in the constellation Lyra, is M57, the famous Ring nebula—the ejected outer atmosphere of a dying star.

D. M51, the Whirlpool galaxy, can be found near the end of the handle of the Big Dipper.

E. With a telescope, you can easily see the hot, massive Trapezium of stars that causes the Orion nebula to glow.

X. A beautiful phenomenon that requires no optical equipment for viewing is the auroras, the northern (or southern) lights.

A. Auroras are produced when charged particles from the Sun are trapped by Earth's magnetic field.

1. They spiral around, gradually approaching the poles, where the magnetic field intersects Earth's atmosphere.

2. When they collide with molecules of air, they kick the electrons to higher energy levels, giving up some of their own energy of motion.
3. The electrons subsequently jump back down to lower levels, emitting *photons* (light).

B. Auroras are especially prominent after major eruptions on the Sun's surface, because unusually large numbers of energetic particles are ejected and can subsequently reach Earth.

C. Auroras can change their appearance from minute to minute, and large differences are visible over tens of minutes.

D. Because the Earth's magnetic field intersects the atmosphere at high latitudes, auroras are best seen far north (or far south) on Earth. Nevertheless, people in the northern United States can generally view several auroral displays per year, especially when the Sun is in an active phase of its 11-year cycle.

E. Astronauts in space often see Earth's auroras.

F. Auroras have also been photographed on Jupiter and Saturn.

Essential Reading:

Dickinson, *The Backyard Astronomer's Guide*, 2nd ed.

Pasachoff, *Peterson's First Guide to Astronomy*.

Supplementary Reading:

Parviainen, http://www.polarimage.fi (auroras, comets, and so on).

Pasachoff and Filippenko, *The Cosmos: Astronomy in the New Millennium*, 2nd ed.

Questions to Consider:

1. Why are artificial satellites in low-Earth orbit visible only in twilight, shortly after sunset and before sunrise, whereas satellites far from Earth are also visible much later during the night?
2. Although planets generally wander from west to east among the stars, what do you think happens when the Earth and a planet are on the same side of the Sun and passing each other in their orbits?

Lecture Three

Recent Discoveries in Our Solar System

Scope: In the past few years, there have been several successful missions to Mars, showing conclusively that its surface had ample running water early in its history. The well-known evidence for primitive life on Mars from the Martian meteorite ALH 84001 is still quite controversial. The Galileo spacecraft studied Jupiter and its major satellites, showing a larger number of active volcanoes on Io than had been seen by Voyager and providing additional evidence for a sub-surface ocean on Europa. Spacecraft have obtained detailed images of asteroids, some of which may eventually collide with Earth. High-resolution, ground-based observations of the planets using the new technique of adaptive optics have also revealed a good deal of information. The discovery of a large number of icy, comet-like objects in the Kuiper Belt, near or beyond the orbit of Neptune, strongly suggests that Pluto is not a true planet but, rather, is an unusually large Kuiper Belt Object.

Outline

I. Mars was in the news a lot during 2003, because in August 2003, it passed closer to Earth than ever before in recorded history.

- **A.** The concern was that major dust storms might arise during this time, which coincides with Martian summer.
- **B.** Mars has also figured prominently in the news the past few years because of several successful (and some unsuccessful) spacecraft missions to Mars, including Mars Odyssey and Mars Global Surveyor.
  - **1.** The most important discovery was the convincing evidence that Mars had extensive running water on its surface early in its history, as had long been suspected.
  - **2.** There are numerous surface features that can be explained only by flowing water, and evidence for subsurface water (permafrost) was found with a special instrument.
  - **3.** Water is also the main component of the permanent polar caps, as opposed to the frozen carbon dioxide ("dry ice") component of the polar caps, which comes and goes seasonally.
  - **4.** Venus is too hot because of the runaway greenhouse effect; Mars is too cold; and Earth is just right (as in "Goldilocks").
  - **5.** Presumably, Mars had a thick atmosphere and running water long ago.
    - **a.** But a cooling trend caused part of it to freeze or, perhaps, part of it evaporated from the planet.
    - **b.** Either way, the loss of carbon dioxide meant that the greenhouse effect became less pronounced, and Mars cooled even more.
    - **c.** This led to the freezing of more carbon dioxide from the atmosphere, resulting in even less greenhouse heating.
    - **d.** Still more carbon dioxide froze, exacerbating the effect.
    - **e.** In essence, then, Mars appears to have undergone the "runaway *inverse* greenhouse effect"—the opposite of what happened on Venus.
- **C.** In 1996, tentative evidence for primitive life was found in the Martian meteorite ALH 84001, which was found in the Antarctic in 1984 and appears to have been blasted away from Mars about 15 million years ago. The case remains quite controversial.
- **D.** Spacecraft images have made it abundantly clear that the famous "face" on Mars is just an oddly shaped hill, not the work of intelligent extraterrestrials.

II. The Galileo spacecraft has spent several years orbiting Jupiter, providing a wealth of information on its atmosphere, especially on the major moons known as the Galilean satellites.

- **A.** Specifically, there is a much larger number of active volcanoes on Io, the moon closest to Jupiter, than was previously suggested from the Voyager spacecraft.
  - **1.** Io is kept partly melted by the varying tidal forces of Jupiter, which release heat because of internal friction.
  - **2.** The tidal forces vary because gravitational interactions between Io and the other Galilean moons force its orbit to be eccentric (elliptical), rather than circular.
  - **3.** Stanton J. Peale (University of California, Santa Barbara) and his colleagues predicted this just before the Voyager spacecraft reached Jupiter in 1979.
- **B.** Some of the volcanoes have also been imaged with the Keck telescope using the sophisticated technique of *adaptive optics*.
  - **1.** Adaptive optics allows observers to compensate for rapid variations in the Earth's turbulent atmosphere, correcting the incoming waves so that they are plane-parallel, rather than jumbled. The resulting images have much higher resolution (clarity).
  - **2.** To accomplish this, the light from a bright star is evaluated many hundreds of times per second, and corrections are sent to a small deformable mirror that exactly cancels the irregularities in the waves.
  - **3.** This technique works as long as the object being studied is bright enough or if a sufficiently bright star is located next to the object.

4. If the object is faint and lacks a bright star along nearly the same line of sight, a laser beam can create a fake star next to it by exciting sodium atoms in the Earth's upper atmosphere.
5. This *laser guide star* technique has been successfully used at the Lick Observatory, the Keck Observatory, and elsewhere.
6. The largest volcanic eruption known in the Solar System was recently imaged with adaptive optics on one of the 10-meter Keck telescopes.

C. The Galileo results for the moon Europa confirm the suggestion, based on previous Voyager data, that Europa's surface consists of water ice that is fractured in many places.
   1. Beneath the surface is an icy slush, with reasonably warm temperatures.
   2. Europa is kept partially melted for the same reason as Io.
   3. There is a chance that indigenous life developed beneath Europa's surface. Future probes will be sent there to search for primitive life (bacteria, microbes).

D. Astronomers have found a total of at least 58 probable moons of Jupiter, and the number is growing rapidly.
   1. There may be hundreds of moons orbiting Jupiter.
   2. As progressively smaller bodies are found, the question of whether to call them "moons" arises. Do the small particles in Jupiter's ring count as moons, for example?
   3. Saturn currently has 30 known moons (12 were found in the year 2000), while Uranus has 21. The true totals are probably considerably larger.
   4. In January 2003, 3 additional moons of Neptune were found, for a total of 11.

III. The changing tilt of Saturn's rings, as viewed from Earth's perspective, has led to beautiful views in 2003. The year 2004 will also be excellent, and 2005, slightly less so.

A. Using adaptive optics on one of the Keck 10-m telescopes, astronomers have studied Titan, Saturn's largest moon, with a resolution higher than that of the Hubble Space Telescope.
   1. Titan has a thick atmosphere consisting primarily of nitrogen molecules, as on Earth (but there is little oxygen in Titan's atmosphere).
   2. The images show clouds whose appearance changes over time.

B. The Cassini mission is on its way to Saturn, with a scheduled arrival in July 2004. A primary goal of the Cassini mission is to send the Huygens probe down to Titan's surface, which might contain lakes of methane mixed with some ethane.

C. Adaptive optics has been used to obtain detailed images of Neptune, showing the changing cloud patterns.
   1. For example, the Great Dark Spot imaged by Voyager in 1989 is now gone.
   2. There is evidence that Neptune's southern hemisphere has gradually been warming up and forming more clouds; we are seeing seasonal changes.

D. Striking new infrared images of Uranus, taken with one of the 8-m units of the Very Large Telescope (VLT) in Chile, nicely show the ring system, which is very difficult to detect at optical wavelengths.

IV. Now we turn to Pluto, the ninth and last planet. Images obtained with the Hubble Space Telescope show vague surface features—some dark and light areas. We can't expect to see details until a spacecraft is sent to Pluto.

A. But is Pluto really a planet?
   1. Pluto's rather eccentric and inclined orbit is peculiar in comparison with the orbits of other planets.
   2. Moreover, Pluto is smaller than the Moon, and its density indicates an icy composition more similar to that of comets than to the terrestrial or giant planets.
   3. Finally, Pluto is close to where we expected to find at least the inner members of the long-hypothesized *Kuiper Belt*, a reservoir of comets.

B. During the past few years, major progress has been made in discovering Kuiper Belt Objects (KBOs) and resolving the puzzle of Pluto's nature and origin.
   1. There are now hundreds of known KBOs, thanks to diligently conducted searches.
   2. Some of the KBOs are quite large. Quaoar, the largest known, is over half the diameter of Pluto itself and was found only recently.

C. All this evidence makes it almost certain that Pluto is fundamentally a KBO, though the largest one known at this time. But there are others of comparable size.
   1. Thus, either Pluto is not a planet or there are many additional planets similar to Pluto.
   2. If other large KBOs had been discovered shortly after Pluto was found, Pluto probably would not have been called a planet—at least not for long.
   3. The asteroids between Mars and Jupiter, for example, had a similar discovery history, but one that was much less spread out in time.
      a. Ceres, the largest one, was found in 1801.
      b. Pallas and Vesta were found in 1802 and 1804.
      c. Hundreds were found in the ensuing years, and tens of thousands are now known to exist.

    - **d.** Astronomers quickly settled on the term *minor planets* or *asteroids*.
  4. None of the asteroids is dynamically dominant—that is, none of them prevents the others from existing in similar orbits, unlike Jupiter or even the Earth. The same is true for the KBOs and Pluto; in that sense, then, we really shouldn't consider Pluto to be a true planet.
  5. One could perhaps use *sphericity* as part of the definition of a planet or, at least, a minor planet.
    - **a.** Most asteroids have an odd shape; they aren't large enough for their own self-gravity to have made them spherical.
    - **b.** Those with a diameter larger than about 400 km (about 6 asteroids) became spherical; we might consider these to be true minor planets (and the rest to be simply asteroids).
    - **c.** In that case, however, Pluto and at least three other known KBOs should be called minor planets as well, giving a total of at least 10 minor planets (and probably quite a few more that are still undiscovered).

D. There has been no official decision yet regarding a change in Pluto's status.

1. Thus, Pluto remains on the list of nine planets, while the other KBOs and the asteroids are not yet official planets.
2. This could change in the future, depending on what the International Astronomical Union decides. (No single planetarium or observatory is allowed to make such decisions.)
3. In any case, most astronomers recognize that Pluto is fundamentally a KBO, its "planetary" status being largely historical baggage.

E. An additional potentially relevant point is that Pluto has a large moon, Charon. At first glance, one might think that this qualifies Pluto to be a true planet.

1. However, such moons are common: About 5% of the known KBOs have a moon, and the moon's mass is often nearly the same as that of the KBO to which it is bound.
2. These pairs probably formed early in the history of the Solar System, as a result of gravitational encounters between several bodies.
3. About 5% of the asteroids have moons, too, but generally the moon is much smaller than the asteroid itself.
4. The moons of asteroids are probably the debris produced by asteroid collisions, in many cases, quite recently.

V. Spacecraft have obtained detailed images of asteroids, providing new information on their composition and history.

A. Specifically, the Near Earth Asteroid Rendezvous (NEAR Shoemaker) mission found that some asteroids, such as Mathilde, have shattered interiors.

1. In a sense, they are like collections of loose rock held together by mutual gravity. Indeed, some astronomers call them *rubble piles*.
2. Presumably, they were shattered by collisions with other asteroids.

B. Other asteroids, however, are solid inside, such as the near-Earth asteroid Eros.

C. We need to worry about asteroids that cross Earth's orbit. Occasionally, devastating collisions occur, destroying much of the life on Earth.

1. The famous Cretaceous/Tertiary extinction of the dinosaurs (and many other organisms) 65 million years ago was probably triggered by an impact of this kind.
2. Large impact craters have been found on Earth's surface, despite the erosion that tends to erase the evidence.
3. Over the next few tens of millions of years, chances are high that a major impact will occur, unless we find ways of preventing this.
4. An asteroid over 1 km in diameter would threaten civilization. Though at the current time, none is known to be on a collision course with Earth, there are probably more than 1000 of them out there, most of which are still undiscovered.
5. Thus, several intensive programs are now underway to find, during the next two decades, about 90% of the potential Earth-crossing asteroids larger than 1 km in diameter.

Essential Reading:

Nine Planets, http://www.seds.org/nineplanets/nineplanets/.

Pasachoff and Filippenko, *The Cosmos: Astronomy in the New Millennium*, 2nd ed.

Supplementary Reading:

Beatty, Peterson, and Chaikin, *The New Solar System*, 4th ed.

Fischer, *Mission Jupiter: The Spectacular Journey of the Galileo Spacecraft*.

Hodge, *Higher than Everest: An Adventurer's Guide to the Solar System*.

Questions to Consider:

1. How do studies of other planets and moons in the Solar System potentially help us understand various aspects of Earth better, such as its climate, surface features, interior, and history?
2. Do you think Pluto should be dethroned from its status as a planet? Why or why not?

Lecture Four

Other Worlds Galore!

Scope: There are now more than 100 known planets around stars other than our Sun (*extrasolar planets*). Most of these have been found by looking for the "wobbles" in a star that are the reflex motion produced by a massive orbiting planet, but in at least two cases, the planet has also been detected as it passed between us and the star, slightly dimming the star's light. Such *transiting planets* offer the possibility of measuring the chemical composition of the planet's atmosphere. Several systems containing more than one planet are now known. Most of the extrasolar planets have strange orbits, either highly eccentric or very close to the star. A few *free-floating planets* have also been found, but it can be difficult to distinguish these from brown dwarfs (failed stars). Several future NASA satellites are being planned to obtain direct images of extrasolar planets and to find examples similar to the Earth. The discovery of numerous extrasolar planets rekindles the age-old question of whether there is life elsewhere in the cosmos.

Outline

I. Astronomers who search for extrasolar planets, or *exoplanets*—planets in orbit around stars other than the Sun—have made tremendous progress in the past few years.

- **A.** In 1995, there were *zero* planets known around other normal stars.
- **B.** As of May 2003, the list has grown to over 100, and it shows no signs of slowing down.
- **C.** Although the discovered planets are massive gas/liquid giants similar to Jupiter, there is a great diversity in their orbital properties.
- **D.** Extrasolar planets generally can't be seen directly—the glare from the star that they orbit overwhelms their light.

II. The easiest way to find planets around normal stars is to use the Doppler effect: the shift in wavelengths of absorption lines due to radial motion of the star.

- **A.** This can be done with long-term monitoring of optical spectra of bright stars.
- **B.** One looks for a periodic *Doppler wobble* of the star (that is, a sinusoidal change in its radial velocity) caused by motion of the planet around it.
  1. Knowing the period and amplitude (maximum change in radial velocity) of the wobble, the mass of the detected planet can be calculated by using Kepler's third law.
  2. Actually, one gets a *minimum* mass for the planet, because the inclination of the orbit is generally not known. The measured radial velocity of the star is only *part* of the total orbital velocity unless the orbital plane is perpendicular to the line of sight (that is, edge-on). Statistically, the correction is roughly a factor of 2.
  3. The spectra must have very high resolution and incredibly precise calibration of wavelengths.
  4. This technique works best for massive planets with small orbits, because the induced *reflex motion* of the star is then sufficiently large to measure.
  5. Even then, the expected shifts are tiny: Jupiter, for example, causes a reflex motion in the Sun of only about 10 m/s. (For comparison, 2 m/s is rapid walking speed.)
  6. Present technology is woefully inadequate to detect planets comparable to Earth in mass and orbital distance.
- **C.** The reigning champion planet hunter is Geoff Marcy at the University of California, Berkeley. He and his team have found a majority of the known extrasolar planets.
  1. Initially, they found planets with the 3-m reflecting telescope at Lick Observatory.
  2. Their work at Lick is continuing, but they are now finding planets more frequently with one of the Keck 10-m telescopes in Hawaii.

III. Most of the known extrasolar planets found thus far have startling properties.

- **A.** Some, like that of 51 Pegasi (the first one found, by Swiss astronomers Didier Queloz and Michel Mayor), are very massive yet have tiny orbits with periods of only a few days. (The planet Mercury, for comparison, has an orbital period of 88 days.)
  1. It is not clear how they could have formed. If these planets are like Jupiter, the gases should never have been captured; if mostly rocky, there is a shortage of raw material. Almost certainly they formed farther out.
  2. They then spiraled inward because of friction with material remaining in the disk. The star may sometimes swallow planets migrating inward in this way.
  3. Gravitational interactions with other planets can also propel a planet into an orbit close to the star, and tidal effects subsequently make it circular.
  4. In some cases, the planets are so close to the star that they must be evaporating.
- **B.** The orbits of other planets are reasonably large but highly eccentric, unlike those of all planets in our Solar System except Pluto.

1. Probably their eccentricity is an indication of previous interactions with other bodies. The planets with which they interacted may have been ejected from the system.
2. Over long periods of time, planetary orbits that appear to be stable actually become chaotic, and eccentricities can arise.
3. Interactions with the protoplanetary disk during the formation process can also produce eccentric orbits.

C. Several systems containing more than one planet are now known.

1. For example, the star Upsilon Andromedae has at least three planets.
2. The star Gliese 876 has two known planets.
3. The star 55 Cancri has at least three planets, two of which have about the orbital distances of Jupiter and Mercury. This system somewhat resembles our Solar System.

D. About 5% of Sun-like stars have a giant planet within 3 astronomical units (where 1 A.U. is the distance of Earth from the Sun).

1. It is estimated that more than 20% of Sun-like stars have giant planets at larger distances.
2. An important recent discovery is that giant planets are much more common around stars that have a high abundance of heavy elements, rather than a low abundance. Apparently, a rocky, Earth-like core forms first, then attracts copious amounts of gas from its surroundings.

E. Are these large objects really planets, or might they be "failed stars" (brown dwarfs) in which there is no sustained nuclear fusion of ordinary hydrogen to helium?

1. The presence of systems of two or more planets argues against the brown-dwarf hypothesis.
2. A plot of the mass distribution shows that small masses (<1 Jupiter mass) dominate, despite the fact that they are harder to find than massive planets that produce larger wobbles in the stars they orbit.
3. The trend probably continues to still smaller masses, but we are limited by the precision of the discovery technique.
4. The large number of relatively low-mass planets argues against the hypothesis that most of these objects are brown dwarfs. The formation processes of planets and brown dwarfs seem to differ.

IV. In at least two cases, an extrasolar planet has been detected as it passed between us and the star it orbits, slightly dimming the star's light.

A. For a transit to happen, the planet's orbital plane must be aligned along our line of sight.

1. Venus transits across the Sun occasionally. This last happened in 1874 and 1882, and it will occur again in 2004 and 2012.
2. Mercury transited across the Sun in 1999 and in 2003.

B. The most convincing extrasolar case is that of HD 209458. The measured light from the star diminished exactly when it was supposed to, according to the already known radial-velocity curve induced by the planet. (That is, we could predict when the light should fade.)

1. Incredibly good data were obtained with the Hubble Space Telescope: The light curve (plot of brightness vs. time) is so good that large moons and rings would have also been detected had they existed around the planet.
2. Some of the light from the star passed through the atmosphere of the planet, thereby opening the possibility that atoms and molecules might produce an absorption line in the star's spectrum.
   - **a.** A weak line of neutron sodium was indeed detected!
   - **b.** This marks the first detection of the atmospheric gases of an extrasolar planet.
3. Such techniques might someday reveal evidence for life on extrasolar planets.
   - **a.** The presence of absorption lines of oxygen and methane, for example, would imply life, because these molecules are highly reactive together and their supply must be continuously restored.
   - **b.** Biological processes are the only known continuous source of these specific gases.

C. The other, less secure, case of a transiting extrasolar planet was announced in January 2003.

D. Astronomers used the Hubble Space Telescope to search for transiting planets in the globular star cluster 47 Tucanae, with negative results.

1. This is perhaps not surprising.
   - **a.** Planets don't easily form if there are many interactions with other stars.
   - **b.** Planets don't easily form around stars with only a small amount of heavy elements (as in globular clusters).
   - **c.** Gravitational interactions among closely spaced stars tend to eject planets that may have formed.
2. Recently, one planet appears to have been found in a globular cluster but not with the transit method.

E. Kepler, a spacecraft to be launched in 2006, will search for transiting planets by monitoring more than 100,000 stars simultaneously for four years. A major goal is to find terrestrial (Earth-like) planets, to see whether our Solar System is typical or a fluke.

1. This will be difficult to achieve, because the cross-sectional area of a terrestrial planet is small compared with the star that it orbits; thus, the amount of dimming is small.
2. Moreover, starspots (similar to sunspots) and other stellar activity can effectively obscure the dimming produced by a transiting

planet. The astronomers want to see at least three transits before concluding that a given planet is present.

3. Kepler and similar missions are worthwhile and should eventually reveal a large number of planets—hopefully, even some terrestrial ones.

V. The existence of *free-floating planets* is probable. (However, because they don't orbit a star, they are not really "planets" in the conventional sense of the word.)

A. Some planets are ejected from planetary systems during gravitational interactions among the planets; they subsequently roam freely among the stars.

B. Some free-floating planets may have formed from the gravitational contraction of gas in much the same way that stars form but with too little mass to undergo nuclear fusion.

C. Recently, several teams of astronomers have claimed to detect free-floating planets, mostly from infrared surveys of star-forming nebulae.

1. Many of these are probably brown dwarfs, not really planets.

2. A few in the Orion nebula and elsewhere seem to have a mass less than 13 Jupiter masses, similar to normal planets.

D. Another technique for finding free-floating planets is to search for gravitational lensing of the light of a star by the planet that passes between the star and us.

1. According to the general theory of relativity, the gravitational field of the planet warps the light from the background star, focusing it toward us and making the star briefly appear brighter.

2. By monitoring a very large number of stars over a substantial amount of time, a few such events might be detected and studied in a statistical manner.

3. The disadvantage is that a given planet should pass between a star and us only very rarely, making it difficult to gain confidence that a planet has been found.

VI. Although the light from a star generally drowns out the feeble reflected light from an orbiting planet, sophisticated new techniques might image planets during the next two decades.

A. One goal of future optical *interferometers*, for example, is to directly detect planets.

1. The trick is to cleverly combine the light from two or more telescopes "out of phase" (that is, destructively), in such a way that the light from the star is largely cancelled.

2. With the glare from the star severely diminished, dim planets should become visible.

B. NASA's Space Interferometry Mission is being planned for launch around 2012, with the anticipation that it will directly detect planets.

C. NASA's Terrestrial Planet Finder is also on the drawing board, specifically for the detection and study of Earth-like planets. We would like to have images of these planets that show some detail, such as continents or clouds.

VII. The discovery of more than 100 extrasolar planets has rekindled the question of whether we are alone in the cosmos.

A. At times, it has been dangerous to voice the opinion that there are other planetary systems with life in them. Giordano Bruno was burned at the stake in Rome in 1600 for believing, "Innumerable suns exist; innumerable earths revolve around these suns in a manner similar to the way the seven planets revolve around our Sun. Living beings inhabit these worlds."

B. Fortunately, we can now freely pursue this question, and we even have some clues regarding where specifically to search for signals from intelligent life.

Essential Reading:

Dorminey, *Distant Wanderers: The Search for Planets beyond the Solar System.*

Pasachoff and Filippenko, *The Cosmos: Astronomy in the New Millennium*, 2^{nd} ed.

Supplementary Reading:

Croswell, *Planet Quest: The Epic Discovery of Alien Solar Systems.*

Extrasolar Planets, http://www.exoplanets.org.

Ferris, *Life Beyond Earth.*

Goldsmith, *Worlds Unnumbered: The Quest to Discover Other Solar Systems.*

Questions to Consider:

1. What are the pros and cons of the different techniques used (or potentially used) to detect and study extrasolar planets?

2. Why can we generally measure only the minimum mass of an extrasolar planet using the Doppler wobble technique?

Lecture Five

The Formation and Evolution of Stars

Scope: Significant progress has been made in our understanding of how stars and planets form within nebulae—giant clouds of gas and dust. Dusty protoplanetary disks have been found around many newly formed stars, and clumps within them may be planets being born. In some harsh environments close to bright stars, intense radiation may inhibit the formation of planets. The angular momentum (spin) of the disk may be eliminated through powerful jets. For decades, the expected number of solar neutrinos, elusive particles that should be created by the nuclear reactions in the Sun, had not been detected. This outstanding problem was recently solved: The solar neutrinos change into other types of neutrinos on their way to Earth, and these other neutrinos can be seen only with new detectors. The results imply that neutrinos have a small but nonzero mass. During the past few years, a large number of brown dwarfs have been found. Often called "failed stars," these objects actually do fuse deuterium (heavy hydrogen) in their cores for a short time. Conjectures about the Sun's future evolution can be made through comparisons with other, more highly evolved stars that have already produced beautiful shells of glowing gas (planetary nebulae) around a dying white dwarf.

Outline

I. Through studies of young stars and stars that are still forming, we now have a better understanding of the formation of the Sun and our Solar System.

- **A.** Stars and planets form in giant clouds of gas and dust (fine particulate matter) that are gravitationally contracting.
  - **1.** These clouds, or *nebulae*, are abundant in our galaxy.
  - **2.** Some of the gas is from previous generations of stars and has been chemically enriched by the fusion processes in stars.
  - **3.** The gas is atomic, but in the densest regions, molecules are present as well; thus, we call these objects *giant molecular clouds*.
- **B.** Some of the giant molecular clouds are so dense that we cannot see through them—they appear dark, because the gas and dust within them block light from stars behind them. These clouds are also called *dark nebulae*.
  - **1.** These clouds are transparent to radio waves and infrared light.
  - **2.** Thus, we can generally peer deeper into a giant molecular cloud by looking at radio and infrared light than through optical studies.
- **C.** About a decade ago, when the great Orion nebula was examined with the Hubble Space Telescope at optical wavelengths, dusty "protoplanetary disks" (*proplyds*) were found around some newly formed (or still forming) stars.
  - **1.** Such disks were theoretically expected, and the discovery delighted astronomers.
  - **2.** However, it was somewhat surprising to find proplyds at optical wavelengths. Apparently, these particular proplyds were obscured relatively little by dense gas and dust, being in the outskirts of the dense nebula.
- **D.** Artist's impressions of the proplyds sometimes showed clumps, which presumably were on their way to forming *planetesimals* ("little planets") and, subsequently, planets.
  - **1.** Such planetesimals were expected, based on theoretical calculations on computers, but a decade ago, there was no direct observational evidence for them.
  - **2.** Recently, however, clumps were found in several proplyds. Presumably, they are on their way to forming planets.
  - **3.** Relatively empty regions in some proplyds may be the voids left over when gas in those regions coalesced to form planets.
- **E.** If two or more planets form at nearly the same distance from the star, gravitational interactions will generally eject all but one object from that region.
  - **1.** The remaining planet is kicked into an eccentric orbit by the interaction.
  - **2.** This may be the origin of the eccentric orbits of many extrasolar planets, as discussed in Lecture Four.
- **F.** We don't yet know what governs the fragmentation of a contracting nebula into many smaller volumes, each of which forms a star.
  - **1.** That is, we cannot tell how many stars will be born in a given cloud and how massive each star will be.
  - **2.** Moreover, we don't fully understand the effects that massive hot stars have on the formation of other stars in their vicinity.
- **G.** There is another problem: getting rid of angular momentum. A spinning, gravitationally contracting cloud should spin progressively faster as it contracts, because of the conservation of angular momentum.
  - **1.** Angular momentum is a measure of the total spin of a system.
    - **a.** It is the product of the mass, radius, and spin rate (speed) of the system.
    - **b.** If the size (radius) decreases and the mass stays the same, the rate of spin must increase.
    - **c.** A familiar example is that of an ice dancer who brings her arms in to spin faster.

2. According to this line of reasoning, stars should be rotating much faster than they actually do. The Sun, for example, rotates about its axis about once per month, a rather slow rate.

3. An important clue comes from images of very young stars, still surrounded by dusty disks, which have two jets emerging in opposite directions along their axis of rotation.

    a. Apparently, the bipolar jets carry away the angular momentum.

    b. The blobs within them are spinning, like a bullet shot out of a rifle, and thus, have angular momentum.

    c. This slows down the rotation rate of the newly forming star.

    d. But we are still not sure how the spinning jets form.

II. During the slow contraction phase, the gas on its way to forming a star releases gravitational energy. The object is called a *pre–main-sequence star* at this stage.

A. Part of the gravitational energy goes into heating the gas, and part is radiated from the surface of the pre–main-sequence star.

1. As energy is radiated, the object continues to contract, and its internal temperature rises.

2. As long as energy is being radiated from the pre–main-sequence star's surface, without a supply of new energy other than gravity, the object must contract and release additional gravitational energy, thereby increasing its temperature and pressure.

B. Eventually, the temperature in the core becomes sufficiently high that nuclear reactions can begin.

1. These reactions release energy, compensating for the loss of energy from the object's surface.

2. The object becomes a full-fledged star, fueled by nuclear fusion.

C. With a steady supply of new energy, there is no longer any reason for the star to contract.

1. It achieves a stable, mechanical balance called *hydrostatic equilibrium*.

2. The outwardly pushing pressure exactly balances the inward force of gravity.

3. The star can remain stable for a long time, releasing energy through nuclear fusion. It is now called a *main-sequence star*.

III. The Sun generates its energy through the fusion of protons into helium nuclei, in a process known as the *proton-proton chain*.

A. The mass of a normal helium nucleus, consisting of two protons and two neutrons, is smaller than that of the four protons (hydrogen nuclei) that went into making it.

1. The mass difference, m, is converted into energy according to Einstein's famous formula, $E = mc^2$. It is called the *binding energy* of the helium nucleus.

2. This is the energy that makes its way through the Sun and is eventually radiated from its surface.

B. As part of the proton-proton chain of reactions, two of the protons turn into neutrons.

1. The relevant reaction is that a proton becomes a neutron, a positron, and a neutrino.

2. A positron (e^+) is an antielectron; it rapidly annihilates with an electron (e^-), producing photons.

3. Neutrinos (ν, but not to be confused with frequency!) are neutral particles that hardly interact with anything at all.

4. The rate of neutrino production in the Sun should be prodigious. A tiny fraction of them interact with matter on Earth and are potentially detectable, enabling us to test the hypothesis that nuclear reactions power the Sun.

5. Ray Davis was the first to conduct extensive, long-term studies of the neutrino detection rate. His experiment ran for about three decades.

    a. He used a huge underground tank of cleaning fluid in the Homestake Gold Mine near Lead, South Dakota. Deep underground, the tanks are shielded from cosmic rays—high-energy particles from space.

    b. When a chlorine nucleus interacts with a neutrino, it forms a nucleus of radioactive argon. This should happen about once per day. However, Davis detected only about one-third of the expected number of argon nuclei.

    c. This is known as the *solar neutrino problem*.

    d. Davis was awarded a share of the 2003 Nobel Prize in Physics for this work.

C. One possible conclusion is that the Sun's core is *not* undergoing nuclear fusion at all or at an unexpectedly small rate.

1. This seemed unlikely, given that the process of elimination strongly suggests that nuclear fusion is responsible for the Sun's energy.

2. However, it was conceivable that the Sun is currently liberating energy from gravitational contraction, even if, normally, fusion is its main energy source.

D. Another possibility was that the actual temperature at the center of the Sun was slightly lower than the estimated value. In this case, the highest-energy neutrinos (from a rare branch of the proton-proton chain) to which Davis's experiment was sensitive would not have been produced in such large quantities.

E. Yet a third possibility is more closely related to fundamental physics rather than astrophysics: Suppose the *electron neutrinos* produced by the Sun change (*oscillate*) into a different type of neutrino (*muon neutrinos* or *tau neutrinos*) during their journey.

1. Only the electron neutrinos were detectable with the experimental apparatus available up through the late-1990s, and this could account for the deficit.
2. It turns out that such oscillations can occur *only if* neutrinos have nonzero mass.
3. If this conclusion is correct, then study of the Sun will have taught us something fundamental about particle physics.

IV. In 1998, an experiment conducted at the Kamioka Mine in Japan provided relatively direct evidence that muon neutrinos do indeed oscillate and have nonzero mass!

A. High-energy protons hitting Earth's atmosphere produce muon neutrinos.

1. These can interact with highly purified water in a giant vessel known as Super-Kamiokande.
2. The interaction produces a flash of light that is detected by phototubes surrounding the water.

B. The result was that muon neutrinos produced by the atmosphere above Super-Kamiokande were detected at the expected rate, whereas muon neutrinos produced by the atmosphere far from Japan, perhaps even on the other side of the Earth, were detected at only half the expected rate.

1. This probably means that the muon neutrinos, on traveling through much of the Earth, change (oscillate) into another kind of neutrino, probably tau neutrinos.
2. Thus, electron neutrinos might undergo oscillations, too.

C. During the past few years, stunning observational evidence that electron neutrinos do indeed change from one type to another was found.

1. The work was done at the Sudbury Neutrino Observatory (SNO) in Canada.
2. By using highly purified *heavy water* or *deuterated water* (water in which the hydrogen is actually deuterium, an isotope of hydrogen consisting of a neutron and a proton bound together), researchers at SNO were able to detect *all* flavors of neutrinos, as well as (separately) electron neutrinos.
3. Their results confirm that only one-third of the expected number of electron neutrinos is found. But when *all* neutrinos are measured, the expected number is found!

D. This magnificent experiment convincingly shows that electron neutrinos do indeed oscillate into muon and/or tau neutrinos and that, therefore, they have mass.

1. Indeed, it appears that fundamentally, nature has three types of neutrinos with a definite mass, to which we will mundanely refer as *Types 1*, *2*, and *3*.
2. However, the *observable* flavors of neutrino are the electron, muon, and tau neutrinos, which are *mixtures* of the fundamental Types 1, 2, and 3.
3. For example, when the quantum waves representing two of the fundamental types (say, Types 1 and 2) are "in phase," we measure one kind of neutrino (say, the electron neutrino). When these two fundamental types are "out of phase," we measure another kind of neutrino (say, the muon neutrino).
4. As an electron neutrino travels through space, its quantum waves go from being in phase to out of phase and back again, so the measured properties of the neutrino change.

E. Theoretically, neutrinos should oscillate faster while they are traveling through the Sun or the Earth than when they are traveling through the vacuum in between.

1. There are some tantalizing signs of this effect in the SNO data: a possible difference in the results obtained when the experiment is on the daytime and nighttime sides of the Earth.
2. More data must be gathered and analyzed before we can be certain, however.

F. The resolution of the solar neutrino mystery is one of the greatest achievements in the past few decades of astrophysics.

1. It tells us that our understanding of the astrophysics of the Sun was correct.
2. It also shows that the "standard model" of elementary particle physics is incomplete, because this model predicts a zero neutrino mass.
3. The nonzero mass of the neutrino also has some cosmological implications, but it is unlikely to change the fate of the Universe because the mass, though nonzero, is still very small.

V. Now that we are convinced that the Sun and other stars generate their energy through nuclear fusion, let us reconsider the case of the *brown dwarfs*, which are supposedly "failed stars."

A. Stars less massive than about 0.070 to 0.075 solar masses (that is, about 70–75 Jupiter masses) do not achieve sustained nuclear fusion of ordinary hydrogen.

1. That is, they don't undergo much fusion of protons via the proton-proton chain.

2. Traditionally, they have been called *brown dwarfs* (though they aren't really brown in color), but for many years, none was found.

3. They are about the size of Jupiter, almost independent of their mass.

B. During the past few years, hundreds of them have been found.

1. A few were identified in high-quality ground-based images (especially with the technique of adaptive optics) or in Hubble Space Telescope images.

2. But being very cool and faint, they are difficult to detect at optical wavelengths.

3. Most were discovered during infrared surveys of the sky.

4. Despite their large numbers, they don't contribute much to the mass of our galaxy, and they cannot account for most of the mysterious *dark matter* in galaxies.

C. However, it turns out that brown dwarfs down to about 13 Jupiter masses *do* fuse heavy hydrogen (deuterium) into helium; deuterium doesn't require such high temperatures and pressures for fusion.

1. Deuterium fusion admittedly doesn't last long, because the cosmic abundance of deuterium is only about 1/100,000 that of ordinary hydrogen (protons); the deuterium gets used up.

2. But in a similar way, one could argue that fusion of ordinary hydrogen lasts only a short time in the most massive stars before they burn out, because they are so massive.

3. Thus, brown dwarfs more massive than about 13 Jupiter masses differ from massive planets or from the free-floating planets (*planetary-mass objects* or *planemos*) discussed in Lecture Four.

VI. What will happen to the Sun as it ages? Having watched other stars in great detail, we have a better understanding of the stages through which our Sun will pass.

A. The Sun's power will gradually increase, and the oceans will have evaporated away within half a billion years. Life on Earth will perish, and certainly, we must leave by then.

B. In 5 to 6 billion years, the Sun will become very large and luminous—a *red giant*.

1. Then, its outer atmosphere of gases will be ejected in a series of relatively slow ejections like "cosmic burps."

2. The exposed hotter, inner layers of the Sun will emit ultraviolet photons that cause the ejected shells of gas to glow.

a. The shell is called a *planetary nebula*, named in this way because they looked like planetary disks to astronomers over a century ago.

b. They can have many intricate patterns, as we have seen in the case of other stars, even if they are spherically symmetric to a first approximation.

c. The details, such as comet-like knots, are probably the result of complex interactions between separate ejections (or "winds") having different speeds and of gas having different densities.

3. In some cases, planetary nebulae are "bipolar," with hourglass-like shapes.

a. We think these are formed when the star is part of a binary system.

b. The first star is already dead (a white dwarf), and when the other star becomes a red giant, it envelopes both stars. A disk forms around the stars, because of the orbit.

c. Gas is then ejected from the system, but it cannot easily escape along the direction of the disk, so it escapes along the orbital axis, forming the observed shape.

d. Our Sun will presumably have a basically spherical shape, because it is a solitary star and is not rotating very rapidly.

Essential Reading:

Pasachoff and Filippenko, *The Cosmos: Astronomy in the New Millennium*, 2nd ed.

Supplementary Reading:

Bahcall, http://www.sns.ias.edu/~jnb/ ("popular accounts" link).

Golub and Pasachoff, *Nearest Star: The Exciting Science of Our Sun*.

Malin, *The Invisible Universe*.

Questions to Consider:

1. A solitary star that is still forming must get rid of its angular momentum through the ejection of spinning jets (and, to some extent, by storing it in planets that form in the disk). Is there as much of a problem for a cloud from which a binary star forms?

2. It is often said that we on Earth have about 5 billion years before we need to worry about the Sun's death (assuming we survive asteroid collisions and other drastic events). Why is this incorrect?

Lecture Six

Supernovae—Catastrophic Stellar Explosions

cope: Some stars end their lives in a violent explosion, literally blowing themselves apart. They create heavy elements that are ejected into the cosmos, becoming the seeds for future stars and planets and, perhaps, of life itself. Our understanding of these exploding stars—*supernovae*—has improved considerably, in part because of the success with which robotic searches have recently found supernovae and in part because of new theoretical work. For example, we now know that massive stars can lose their hydrogen (and, sometimes, even their helium) envelope before exploding, through the collapse of their core and the ejection of the surrounding layers. As in the case of hydrogen-rich Type II supernovae, such a "stripped" supernova undergoes core collapse and ejection of the surrounding layers, producing a neutron star. They are fundamentally different from exploding white dwarfs, which undergo a thermonuclear runaway. However, we still don't understand the manner in which a white dwarf reaches a critical unstable mass before exploding as a Type Ia supernova. Some kinds of massive stars undergo large eruptions before exploding, becoming much brighter and masquerading as supernovae.

Outline

I. Most stars, including the Sun, end their lives rather quietly as white dwarfs, after expelling their outer layers to form planetary nebulae.

  A. The white dwarf is the denuded core of the star.

    1. It consists of a strange substance called *degenerate matter*, governed by the laws of quantum physics.

    2. Because no more nuclear reactions occur within the white dwarf, it radiates its stored energy, gradually cooling and becoming very faint.

  B. Some stars, however, violently destroy themselves by exploding. Among the main characteristics of the explosions are the following:

    1. The ejected gases expand with speeds that can exceed 10,000 km/s.

    2. Over the course of a few days or weeks, they become much more luminous at visible wavelengths—up to 10 billion times the solar luminosity.

    3. For a few weeks, they can rival the brightness of a small galaxy!

    4. They fade over the course of years.

  C. Supernovae are important for many reasons. (See *Understanding the Universe*, 1998.) From a human perspective, however, supernovae are most important because they produce and disperse heavy elements into the cosmos.

    1. The elements are synthesized by nuclear fusion before and during the explosion.

    2. The ejected gases expand, producing supernova remnants, like the Crab nebula from the explosion of 1054 A.D.

    3. After tens of thousands of years, the chemically enriched gases merge with other clouds of gas.

    4. If a sufficiently large cloud is produced, it can gravitationally contract to form chemically enriched stars and planets.

    5. In the case of our own Solar System, life arose on at least one planet. The same might happen elsewhere in our galaxy and others.

    6. The oxygen that we breathe, the carbon in living tissue, the calcium in our bones, the iron in our red blood cells, and the gold and silver in our jewelry were produced long ago, deep inside stars.

    7. Thus, as Carl Sagan was fond of saying, "We are made of star stuff."

II. Supernovae are rare: They occur perhaps once per century in a typical galaxy. We must examine thousands of galaxies per year to have a few dozen to study each year.

  A. Some amateur astronomers, such as the Rev. Robert Evans in Australia, find them visually by looking through telescopes.

  B. At UC Berkeley, a 0.75-meter robotic telescope (the Katzman Automatic Imaging Telescope) at Lick Observatory obtains charge-coupled device CCD images of more than 1000 galaxies each night.

    1. The images are automatically compared with old ones, and apparently "new" stars are supernova candidates.

    2. Undergraduate students examine these candidates and eliminate the bad ones.

  C. The Lick Observatory Supernova Search is by far the world's leading search for relatively nearby supernovae.

    1. One was found in 1997 (SN 1997bs, where the numbering scheme in a given year starts with "A," goes through "Z," then goes to "aa" through "az," then "ba through bz," and so on).

    2. Twenty were found in 1998 (a world record in a single calendar year). Then, we found 40 in 1999, 38 in 2000, 68 in 2001, 82 in 2002, and 37 through 28 May 2003.

  D. The brightness of supernovae is monitored through different filters (blue, visual [green], red, and near-infrared). The resulting *light curves* (plots of brightness vs. time) tell us about the physics of the explosion, and we can look for trends.

E. It is also important to obtain a spectrum of each supernova, as many times as possible over the course of its evolution. This is done primarily with the 3-m reflector at Lick Observatory and with the Keck 10-m telescopes in Hawaii.

III. There are two main types of exploding stars.

- **A.** Those that show hydrogen (H) in their spectra are called Type II.
- **B.** Those that do *not* show hydrogen in their spectra are called Type I, which are further subdivided into Types Ia, Ib, and Ic.
  - **1.** Type Ia supernovae have a strong absorption line in the red part of the spectrum attributed to silicon atoms. These are the objects formerly known simply as *Type I*, before the other two subclasses had been recognized.
  - **2.** Type Ib supernovae lack the strong silicon absorption line but exhibit lines of helium instead.
  - **3.** Type Ic supernovae lack the silicon and helium lines. However, they do show lines of calcium, oxygen, and some other elements.
  - **4.** There are also a few “hybrid” types, as discussed below.
- **C.** Besides the spectra, there are other differences as well, such as in the light curves of different supernovae.

IV. Type Ia supernovae occur in all kinds of galaxies, including elliptical galaxies that have few if any massive stars.

- **A.** Thus, their “progenitors” (the stars that produce them) are old, or reasonably old—ages of perhaps a few hundred million to a few billion years.
- **B.** A Type Ia supernova is thought to be produced by a white dwarf in a binary system, but only a small fraction of such systems have the properties necessary to yield an explosion.
  - **1.** If the companion star is sufficiently close to the white dwarf, gas from its outer envelope can flow from the companion to the white dwarf.
  - **2.** If the mass of the white dwarf reaches a critical value of about 1.4 solar masses (known as the *Chandrasekhar limit*), the white dwarf becomes unstable, and a series of uncontrolled nuclear reactions ensues.
  - **3.** Heavy elements are synthesized from carbon and oxygen, thereby liberating a huge amount of energy. This unbinds the star, and it explodes, leaving no compact remnant.
- **C.** Although this basic picture for the explosion of a Type Ia supernova seems fairly secure, the exact nature of the companion star is unclear.
  - **1.** One problem is that if the companion star were a normal star donating *hydrogen* to the white dwarf, why don’t we see any hydrogen in the spectrum?

  - **2.** Perhaps the companion star is another white dwarf that is *not* transferring material slowly to the original white dwarf.
    - **a.** If the two white dwarfs are sufficiently close together, they will gradually spiral toward each other as they emit gravitational radiation.
    - **b.** Eventually, the less massive white dwarf will be ripped apart by tidal forces, forming a disk of material around the more massive white dwarf.
    - **c.** As material from the disk falls onto the white dwarf, its mass grows, and the white dwarf explodes when the mass reaches the Chandrasekhar limit.
    - **d.** One problem with this scenario is that very few closely spaced white dwarfs pairs have been found, despite extensive searches.
  - **3.** These and other problems suggest that some Type Ia supernovae result from the explosions of white dwarfs that *don’t* reach the Chandrasekhar limit.
    - **a.** If an explosion could occur at sub-Chandrasekhar masses, then there would be many more candidate systems in our galaxy and others that could produce Type Ia supernovae.
    - **b.** If little or no hydrogen is being accreted from the companion star, hydrogen might not be visible in the spectrum of the supernova.
    - **c.** Unfortunately, detailed modeling of the expected light curves and spectra of such systems do not support this hypothesis: The predictions don’t agree with observed properties of Type Ia supernovae.

V. Type II supernovae arise from stars at least 10 times the mass of the Sun (but, in some cases, perhaps 8 to 10 times the mass of the Sun).

- **A.** Near the end of its life, a star initially more than 10 times the mass of the Sun becomes a supergiant—generally a cool red one.
- **B.** It develops an internal structure similar to that of an onion: There are layers of progressively heavier elements going in from the outer atmosphere to the core, with iron in the very center.
  - **1.** The heavy elements were synthesized by fusion of lighter elements.
  - **2.** Effectively, the ashes of one set of nuclear reactions became the fuel for the next set, liberating energy at each stage and keeping the star hot inside.
- **C.** The iron core cannot fuse to form heavier elements, because energy would be absorbed rather than liberated, accelerating the demise of the star. Iron and elements of similar mass have the most tightly bound nuclei.

D. The mass of the iron core increases because of nuclear fusion in the surrounding shell.
  1. When it reaches about 1.4 solar masses (similar to the Chandrasekhar limit of a white dwarf), it becomes unstable and collapses to form a neutron star.
  2. The collapsing core overshoots its equilibrium size and rebounds outward, like someone jumping onto a trampoline.
    a. It collides with the inward-falling surrounding layers and propels them outward.
    b. For a stunning analogy, hold a tennis ball on top of a basketball several feet above the ground and drop both of them simultaneously. The tennis ball will rebound to a great height.
    c. The collapsed core also emits an avalanche of neutrinos, some of which interact with the surrounding layers and push them out. This is actually more important than the mechanical "bounce" described above.

E. Our theory of Type II supernova explosions was solidly tested with observations of SN 1987A, which was in a galaxy only 170,000 light years away.
  1. Neutrinos from the collapsed core were detected by the Kamiokande experiment in Japan and elsewhere.
  2. Evidence for newly synthesized heavy elements was found.
  3. The progenitor star was indeed a supergiant, but it showed evidence of previous, relatively gentle episodes of mass loss, similar to the process by which less massive stars produce planetary nebulae.
    a. A ring of material, believed to originally have been part of the star, is visible around the supernova.
    b. The supernova ejecta are beginning to crash into the ring, causing it to light up in many spots.
    c. In a few years, the supernova remnant will brighten substantially, as collision progresses.

VI. It turns out that the Type Ib and Ic supernovae are closely related to Type II supernovae in the physical characteristics and explosion mechanism, despite having spectra that superficially resemble those of Type Ia supernovae.

A. Some massive stars are able to get rid of their outer atmosphere of gases through winds and small eruptions near the ends of their lives, similar to (but more extensive than) the process mentioned above for the progenitor of SN 1987A.

B. A massive star can also sometimes eliminate its outer atmosphere by transferring material to a companion star that is gravitationally bound to it in a binary system.

C. The interior of the massive star continues to evolve in the normal manner, eventually producing an iron core.
  1. When the iron core collapses and the surrounding gases rebound, as described above, a supernova is produced.
  2. If the massive star lacks its outer layer of hydrogen, but the next layer (helium) is still present, then its spectrum will be that of a Type Ib supernova.
  3. If the massive star lacks both hydrogen and helium, having an outer later of carbon and oxygen, then its spectrum will be that of a Type Ic supernova.

D. There is evidence that Type II and Type Ib/Ic supernovae are related in this manner.
  1. A thoroughly observed example was SN 1993J. It was only about 10 or 11 million light years away, in the spiral galaxy M81.
  2. The initial spectra showed hydrogen.
  3. Then, the hydrogen grew weaker and helium appeared.
  4. Finally, the spectrum was dominated by light from heavier elements, such as oxygen and magnesium, which are abundant in the interiors of evolved, massive stars.

VII. In the past few years, it has become increasingly clear that some Type II supernovae are not "genuine" supernovae, defined to be the colossal explosions of stars at the end of their lives.

A. Instead, these particular objects seem to be vigorous eruptions (but not complete explosions) of extremely massive, evolved stars.
  1. The classic nearby case is Eta Carinae, in the southern hemisphere.
  2. In the 19th century, it suddenly became the brightest star in the sky for a short time.
  3. Photographs with the Hubble Space Telescope now show two bubbles of gas expanding from a common origin.

B. An example from research at Lick Observatory appears to be the first "supernova" discovered, SN 1997bs. But this object may not have been a genuine supernova.

C. A beautiful, possibly related type of outburst was that of V838, a star that recently brightened very suddenly.
  1. The outburst lit up many shells of gas from previous eruptions that expelled material.
    a. *Light echoes* were seen from these shells.
    b. The light echoes evolved with time, as we watched different shells of gas being lit up.
    c. Curiously, this particular outburst appears *not* to have released a shell of gas.
  2. The star grew to a size comparable to the orbit of Jupiter but subsequently shrank.

VIII. We think that the collapse of a massive star generally produces a neutron star.

- **A.** A neutron star has a mass of about 1.4 solar masses and a radius of about 10 miles.
  - **1.** Its density (mass per unit volume) is stupendous, like nuclear densities.
  - **2.** In essence, protons and electrons have combined to form neutrons and neutrinos (but the neutrinos quickly escape).
  - **3.** A neutron star is like a gigantic atomic nucleus but consisting mostly of neutrons.
- **B.** Neutron stars have been most often detected in the form of pulsars.
  - **1.** A neutron star's strong magnetic field channels particles into two oppositely directed beams that emit radiation.
  - **2.** If the magnetic and rotation axes are not coincident, the beam on each side sweeps out a cone in space.
  - **3.** If the Earth is sometimes along the beam's line of sight, we will see a flash of light every time the beam points at us. This is very similar to the *lighthouse effect*.
  - **4.** The brightest radiation from a pulsar is generally radio waves, but some young pulsars (such as in the Crab nebula) pulse in optical light or even X-rays.
- **C.** As they cool, the youngest neutron stars can also emit optical light and X-rays from their surfaces (rather than the pulsar beam).
  - **1.** The expected rate of cooling can be calculated, given an assumed internal composition for a neutron star.
  - **2.** At least one young neutron star, however, is cooler than had been expected given its age.
    - **a.** This suggests that its interior consists largely of particles other than neutrons.
    - **b.** Exotic particles, such as kaons and pions, have been suggested.
    - **c.** This is yet another example of astrophysics providing valuable information for particle physicists.

Essential Reading:

Marschall, *The Supernova Story.*

Pasachoff and Filippenko, *The Cosmos: Astronomy in the New Millennium*, 2nd ed.

Supplementary Reading:

Filippenko, in *The Origin and Evolution of the Universe.*

Kirshner, *The Extravagant Universe: Exploding Stars, Dark Energy, and the Accelerating Cosmos.*

Supernovae, http://www-cfa.harvard.edu/oir/Research/supernova/SNlinks.html.

Questions to Consider:

1. Most white dwarfs have a mass of about 0.5 to 0.6 times the mass of the Sun. Does this pose a problem for the hypothesis that most Type Ia supernovae arise from the explosion of a merged white dwarf whose mass reaches the Chandrasekhar limit?
2. If one out of every few thousand people on Earth experienced a real interaction between a neutrino from SN 1987A and his or her body, about how large did the Kamioka water tank have to be to have registered ten such interactions?

Lecture Seven

Gamma Ray Bursts and the Birth of Black Holes

Scope: Roughly once per day, somewhere in the sky, there is a short, intense burst of gamma rays—photons with even higher energies than X-rays. These bursts are distributed uniformly in the sky. For many years, one hypothesis was that these gamma-ray bursts (GRBs) came from a large halo around our galaxy, but another idea was that most of them originate in galaxies billions of light years away. Extensive new data conclusively support the hypothesis that most of them originate in galaxies billions of light years away, showing that GRBs can be the most powerful explosions in the Universe. Some GRBs appear to be associated with supernovae, but the massive star's core collapses to directly form a black hole rather than a neutron star. If a jet of very high-speed particles forms along the rotation axis, it can generate gamma rays and other radiation as a result of collisions with internal and external matter. Other GRBs may arise from the merging of two neutron stars or of a neutron star and a black hole, again producing a relativistic jet of material pointing toward us. It is conceivable that some GRBs are produced when a young neutron star collapses to form a black hole.

Outline

I. The story of gamma-ray bursts (GRBs) is one of the most exciting and intriguing in all of astrophysics, and in the past five years, incredible progress has been made in our understanding of these objects.

- **A.** In the late 1960s, military satellites were scanning the skies, searching for illegal tests of nuclear bombs in space. What they detected was quite surprising.
  - **1.** There were indeed bursts of gamma rays, but their properties were unlike those expected from nuclear bombs.
  - **2.** Other examples of such GRBs were soon seen, but again, they seemed inconsistent with the explosions of nuclear bombs.
  - **3.** It was found that at least one GRB goes off somewhere (at random) in the sky each day.
- **B.** As the data gradually accumulated, it became clear that GRBs were not associated with the plane of our galaxy, unlike most bright stars or neutron stars (pulsars).
  - **1.** Instead, the GRBs are scattered randomly throughout the sky; their distribution is uniform, or *isotropic*.
  - **2.** Data from the Burst and Transient Source Experiment (BATSE) aboard NASA's Compton Gamma-Ray Observatory (CGRO) were especially compelling, with about 2700 detected GRBs.

  - **3.** This meant that GRBs come from either a very large, spherical halo of our galaxy or from far outside our galaxy, perhaps from galaxies billions of light years away.
- **C.** One possibility was that GRBs are mini–black holes, exploding in a burst of radiation because of the Hawking quantum evaporation process. (See *Understanding the Universe*, 1998.)
  - **1.** However, their observed properties didn't agree with predictions.
  - **2.** For example, GRBs flicker substantially in gamma-ray brightness and each of them is unique; such behavior is not expected of exploding black holes.
- **D.** GRBs generally fall into one of two categories.
  - **1.** "Short" bursts that last <2 seconds (typically 0.3 seconds).
  - **2.** The much more numerous "long" ones whose duration is typically 20 seconds (but sometimes up to several minutes).
  - **3.** A few GRBs are on the boundary between these classes, with durations of a few seconds.
- **E.** BATSE, like other gamma-ray telescopes, didn't give accurate positions for the GRBs.
  - **1.** Thus, it was hard to identify them at other wavelengths: Astronomers didn't know where to look with the generally rather small fields of view of their ground-based telescopes.
  - **2.** Without additional observational constraints, there were many different GRB models.

II. A breakthrough came in 1996, with the launch of the X-ray telescope BeppoSAX.

- **A.** It was able to detect and pinpoint X-rays coming from the GRB in an "afterglow" that seems to persist from hours to weeks.
- **B.** Ground-based optical astronomers took photographs of the sky at the accurate positions provided by BeppoSAX.
  - **1.** They found that GRBs are located in faint galaxies, and spectra of these galaxies showed that they are generally billions of light years away!
  - **2.** Thus, the GRBs must be incredibly powerful to appear as bright as they do from such large distances.
- **C.** Radio astronomers also observed the positions provided by BeppoSAX.
  - **1.** One of the first objects observed, GRB 970508 (named in this manner because it was discovered on May 8, 1997), gave a very important clue.
  - **2.** Initially, it showed radio "twinkling" analogous to optical twinkling of stars.

3. After a few weeks, however, the radio twinkling stopped. The interpretation was that the object had grown large enough to show a disk (like a planet), which doesn't twinkle as much.
4. To form a resolvable disk at such a large distance, the material must have expanded with speeds close to that of light: *relativistic speeds*.

D. The power of GRBs (about a million, million suns) can be appreciated by the fact that the optical afterglow of one object, GRB 990123, was detected with small telephoto lenses taking photographs of the sky, yet the object was billions of light years away.

III. Astronomers wanted to study many GRBs to learn more about their characteristics, but BeppoSAX lasted only a few years.

A. A new satellite, HETE-2, now detects GRBs and quickly determines accurate positions.

B. The positions are immediately relayed to various ground-based observatories via the Internet.

C. The robotic telescope (the Katzman Automatic Imaging Telescope) at Lick Observatory receives the information.

1. It can almost immediately stop what it's doing and slew over to the GRB position.
2. A succession of images is automatically obtained at the purported GRB location, to attempt a detection of the optical afterglow and to measure its light curve.
3. We have achieved excellent success in several cases. One object was observed to fade by a factor of 100 in only 20 minutes.

D. Robotic telescopes are playing an increasingly important role in GRB research.

IV. Analysis of the existing data showed that the radiation from GRBs is almost certainly highly beamed—it cannot be emitted isotropically (that is, uniformly over the sky).

A. A leading hypothesis known as the *fireball model* has emerged.

1. Some sort of compact "engine" releases blobs of material at relativistic speeds, along a narrow "jet."
2. Rapidly moving blobs overtake more slowly moving ones, creating internal shocks within the jet that release gamma rays.
3. When the blobs subsequently collide with the circumstellar medium or the interstellar medium (gas in space), external shocks are formed that emit the afterglow visible at wavelengths other than gamma rays.
4. The afterglow fades with time as the shock's energy dissipates.

B. How is the relativistic jet formed? A clue comes from the fact that GRBs often appear in galaxies undergoing vigorous bursts of massive-star formation.

1. Because massive stars live only short lives, such stars are also dying in those galaxies.
2. The jet may have something to do with the rotation of the massive collapsing star known as a *collapsar*.
3. Note that strictly speaking, the collapsar model applies only to long-duration GRBs, because we have not yet pinpointed the locations of short-duration GRBs.

C. If a massive star is rotating just before its core collapses, the collapsed part will spin even faster because of conservation of angular momentum.

1. A disk will form, as in the formation of planetary systems or spiral galaxies.
2. Because escaping material has a hard time going through the disk, it goes along the axis of rotation instead.
3. If the star does not have a thick envelope, the material might burst all the way through the envelope.
   - **a.** Recall that massive stars without hydrogen envelopes, or even without helium envelopes, were discussed in Lecture Six as the progenitors of Type Ib and Ic supernovae.
   - **b.** Thus, perhaps some GRBs are essentially these kinds of supernovae, but with the core collapsing all the way to form a rapidly rotating black hole instead of just a neutron star, thereby releasing an even larger amount of gravitational energy.
   - **c.** The rotation energy of the black hole and the surrounding disk might also be tapped.
4. If the jet breaks through the star's surface and happens to be pointing at Earth, we will see an incredibly bright flash, especially because the brightness of relativistic material moving along the line of sight is enhanced.
5. Spectra of a few GRBs provide evidence for material in the vicinity of the GRBs that was shed by a massive star before its collapse.

D. Extremely recent evidence, gathered serendipitously with a satellite that was studying solar flares, suggests that the jet forms as a result of acceleration of particles along a very strong, highly structured magnetic field.

E. An expectation in the collapsar model is that a supernova should become visible at the location of the GRB after the GRB afterglow has faded sufficiently.

1. A bright supernova, SN 1998bw, did indeed seem to be associated with an unusually faint GRB detected in 1998, but many astronomers thought it might not be representative of long-duration GRBs.
2. Some GRBs show a "bump" in their optical light curve that might be produced by supernova light.
3. Compelling evidence that at least some long-duration GRBs are associated with supernovae was provided by GRB 030329.
    a. The optical spectrum of the bump in the light curve was very similar to that of SN 1998bw.
    b. The spectrum resembles that of Type Ic supernovae, but perhaps with even more highly stripped progenitors than usual.
    c. These observations support the collapsar model.

V. There are some other viable models for GRBs, especially the short-duration bursts that have not been observed extensively.

A. A binary neutron star system could emit gravitational waves and merge.
1. The neutron stars would become torn apart near the final stages of merging, forming a disk with an axis of rotation.
2. A jet of relativistic particles and radiation could emerge along the axis.

B. A neutron star and a black hole in a binary system could merge, as above, forming a jet.

C. It is conceivable that a supernova *precedes* the GRB in some cases when a massive star collapses.
1. This is known as the *supranova model*.
2. The neutron star is initially stable but subsequently collapses to form a black hole.
    a. The star may have become unstable because of accretion of extra matter from its surroundings.
    b. Or it may have become unstable as its rotation slowed.
3. There is some claimed evidence in favor of the supranova model for a few GRBs, but this is still controversial.

D. Much more progress in understanding GRBs will probably be made in the next few years, because an improved NASA satellite (Swift) will find and study many of them.

E. GRBs go off in a typical galaxy once per 20,000 years, but only planets along the very narrow beam are sterilized; hence, most of the galaxy is not affected.

Essential Reading:

Katz, *The Biggest Bangs: The Mystery of Gamma-Ray Bursts, the Most Violent Explosions in the Universe.*

Schilling, *Flash! The Hunt for the Biggest Explosions in the Universe.*

Supplementary Reading:

Pasachoff and Filippenko, *The Cosmos: Astronomy in the New Millennium*, 2nd ed.

Wheeler, *Cosmic Catastrophes: Supernovae, Gamma-Ray Bursts, and Adventures in Hyperspace.*

Questions to Consider:

1. If GRBs are beamed, are the energy requirements per GRB smaller than if isotropic emission (i.e., uniform across the sky) is assumed? Is the number of GRBs that we detect per galaxy affected by the beaming?
2. If short-duration GRBs turn out not to be associated with vigorously star-forming galaxies, which of the proposed models of GRBs will be disfavored?

Lecture Eight

Observational Evidence for Black Holes

Scope: There is now excellent evidence for the existence of stellar-mass black holes in binary systems. The very compact black-hole remnant of a collapsed star orbits another, more normal star, observations of which can be used to determine the black hole's mass. Some progress has been made in showing that black-hole candidates do indeed have *event horizons* from within which nothing can escape, in contrast to neutron stars having hard surfaces. The evidence for supermassive black holes, with masses of millions to billions times that of the Sun, is also quite compelling. These reside at the centers of galaxies, and their mass seems to be related to the mass of the galaxy's stellar bulge. By far the most convincing case is the supermassive black hole at the center of our Milky Way galaxy: Individual stars have been seen orbiting it. There is also a new class of intermediate-mass black holes, 100 to 10,000 times the Sun's mass, that seem to reside in the centers of dense star clusters. The evidence for supermassive black holes in active galaxies and quasars has been growing. When galaxies merge, their central black holes can also coalesce and grow.

Outline

I. We would like to have better evidence for black holes, given that the GRB field is still so young and the ideas are speculative.

- **A.** A black hole is a region of space where the local gravitational field is so strong that nothing, not even light, can escape.
  - **1.** You can imagine compressing the Earth more and more (or progressively increasing the Earth's mass), and the *escape velocity* rises.
  - **2.** This is the speed at which you would need to throw an apple for it to never fall back down.
  - **3.** If the gravitational field becomes so strong that the escape velocity reaches or exceeds the speed of light, not even light will escape.
- **B.** Matter that falls into a black hole (that is, beyond the event horizon of the black hole) gets compressed into a singularity at the center.
  - **1.** Classically, the singularity is a point of infinite density.
  - **2.** Quantum effects probably make its size nonzero; hence, the density is not formally infinite.
  - **3.** While falling into a black hole, an object gets stretched by the immense tidal forces, a process informally known as *spaghettification.*

- **C.** A black hole appears black: It does not emit, transmit, or reflect light. Thus, black holes are difficult to detect.
  - **1.** One cannot simply say that a dark region in the sky is a black hole; there may, instead, simply be no stars in that area.
  - **2.** However, the gravitational influence of a black hole can be seen on objects near it.

II. One can detect a stellar-mass black hole in our Milky Way galaxy by measuring the period and orbital speed of a normal star gravitationally bound to it.

- **A.** But of all the stars in the sky, which ones might be in orbit around a black hole?
- **B.** Stars that emit sudden bursts of X-rays are good candidates.
  - **1.** Matter torn away from a normal star can become part of an accretion disk around a companion black hole or neutron star, and it gets heated to high temperatures.
  - **2.** X-rays are emitted, especially if a clump of material falls onto (or is formed in) the disk.
  - **3.** The X-rays are a signature of a very strong gravitational field. Matter does not gain enough kinetic energy in a weak field; hence, it emits longer wavelengths of light.
  - **4.** X-ray–emitting binary stars were among the first objects detected after the development of X-ray telescopes and X-ray astronomy, work largely done by Riccardo Giacconi, for which he was awarded a share of the 2002 Nobel Prize in Physics.
- **C.** Repeated spectroscopic measurements of the visible star yield its radial velocity as a function of time.
  - **1.** In some cases, a clear sinusoidal variation is found.
    - **a.** The period and amplitude of the radial velocity variations can be measured.
    - **b.** From these, the minimum mass of the invisible companion can be calculated.
  - **2.** If the invisible companion's mass is at least 3 solar masses, it is a good candidate for a black hole by the process of elimination.
    - **a.** It cannot be a white dwarf or a neutron star (too massive).
    - **b.** A normal star of that mass would be very bright.
- **D.** A more accurate estimate of the mass can be made if the inclination of the system is known.
  - **1.** Information about the inclination can be obtained by measuring the apparent brightness of the visible star over the course of its orbit around the black hole.
    - **a.** The black hole distorts the shape of the star into that of a pear or a teardrop.

        - **b.** As the star orbits the black hole, it presents a varying cross-sectional area as viewed by us, except if it orbits in the plane of the sky.
        - **c.** The star appears brighter when we see a larger cross-sectional area and dimmer when we see a smaller cross-sectional area.
    - **2.** The difference between the bright and faint extremes depends on the inclination of the orbit to our line of sight. It is zero if the orbit is in the plane of the sky, and it is the maximum possible variation if the orbit is edge-on to our line of sight.
- **E.** A method for getting the relative masses in some binary systems is to watch the accretion disk around the black hole wobbling around as the black hole and the visible star orbit their common center of mass.
    - **1.** This is done by measuring the wavelength of the center of a strong emission line throughout an orbital period.
    - **2.** The ratio of the maximum radial velocity of the black hole to the maximum radial velocity of the visible star is equal to the inverse of the ratio of their respective masses.
- **F.** By May 2003, about a dozen X-ray binary systems had been found in which the mass of the invisible object is at least 3 solar masses and is, therefore, probably a black hole.
- **G.** Evidence that at least some stellar-mass black holes form during the course of a supernova explosion has recently been found.
    - **1.** In one case, spectra of the visible star reveal substantial quantities of oxygen and other elements thought to be ejected during the explosion of a massive star.
        - **a.** Presumably the supernova ejecta contaminated its outer atmosphere.
        - **b.** The remaining material continued collapsing and formed the black hole.
    - **2.** There is tantalizing evidence that a black hole may now lurk at the location of SN 1987A.
        - **a.** Although a neutrino burst (signifying the creating of a neutron star) was seen at the time of the explosion, no neutron star has been detected since then.
        - **b.** Perhaps the neutron star produced by SN 1987A subsequently collapsed to form a black hole, but we aren't sure yet.
- **H.** In the past few years, evidence may have been found for the presence of an event horizon.
    - **1.** Matter accreting from the companion star in binary systems where the compact object is thought to be a neutron star emits much energy when it hits the surface of the star. The X-rays have been detected with telescopes, such as the Chandra X-ray Observatory.
    - **2.** In contrast, matter accreting from the companion star in binary systems where the compact object is thought to be a black hole never hits a surface but, rather, disappears beyond the event horizon of the black hole. Such systems don't emit as many X-rays, consistent with what we see.
    - **3.** Also, the increasing gravitational redshift and gradual fading of a blob of material falling into one black hole may have been detected.

III. Convincing evidence for *supermassive black holes* (millions to billions of solar masses) has been found in the nuclei of many normal galaxies from the very rapid motions of stars in central clusters.

- **A.** The best case is the center of our Milky Way galaxy, which can be observed in great detail at infrared wavelengths.
    - **1.** The radial velocities of stars are measured from the Doppler shift of lines in their spectra, and the motions along the plane of the sky are determined by repeatedly obtaining images of the stars, showing their positions as a function of time.
    - **2.** The data are now so good and have been obtained for such a long time (about a decade), that stellar *orbits* have actually been tracked.
        - **a.** A few stars pass particularly close to the center of our galaxy, zooming around it.
        - **b.** By applying Newton's laws of motion, the mass of the central object can be calculated, and it turns out to be about 2.5 million solar masses—all within a very small volume.
        - **c.** The calculated density cannot be explained by anything other than a supermassive black hole.
- **B.** The second best case for a supermassive black hole is the spiral galaxy NGC 4258.
    - **1.** There is an accretion disk around the putative black hole, oriented nearly edge-on to our line of sight.
    - **2.** Gas in the disk produces emission lines in the radio (microwave) region of the spectrum, and their Doppler shift has been measured accurately.
    - **3.** The radial velocity as a function of distance from the center behaves exactly as it should if there is a black hole in the center, having 40 million solar masses.
- **C.** Rapid motions have been measured in the centers of many normal galaxies over the past few years, especially with the Hubble Space Telescope.
    - **1.** In those cases where the data are of sufficiently high quality, evidence for a large amount of mass within a small volume has been found.
    - **2.** The calculated masses are millions or even billions of solar masses, within a volume of radius no more than 10 light years (possibly much smaller).

3. The smallest black hole mass measured in one galaxy was about 60,000 solar masses.

D. Over the past few years, some amazing trends have been found.

1. The mass of the central black hole is proportional to the mass of the bulge in a spiral galaxy or to the total mass of an elliptical galaxy.
    - **a.** The bulges of spiral galaxies are old, as are elliptical galaxies (which resemble the bulges of spiral galaxies).
    - **b.** Thus, there is evidence that the formation of the supermassive black hole is related to the earliest stages of the formation of galaxies.
2. Studies also show that for a given bulge mass, the more compact the bulge, the more massive the black hole, suggesting an even closer link between bulge formation and black-hole formation.

E. Evidence for an intermediate-mass black hole, 20,000 times the Sun's mass, was recently found in the center of a globular cluster in the Andromeda galaxy, M31.

1. Another, more controversial case is the possible black hole in M15, a globular cluster in our galaxy: It may have 1500–1700 solar masses.
2. These objects extend the bulge mass/black-hole mass correlation to even smaller masses.
3. If real, they help bridge the gap between stellar-mass black holes and supermassive black holes.
4. Stars in the immediate vicinity of a black hole can be tidally disrupted (torn apart) and, subsequently, swallowed (accreted) by the black hole.

IV. It has long been thought that quasars, incredibly luminous and very distant objects, are powered by the accretion of matter (perhaps from tidally disrupted stars) into a supermassive black hole at the center of a galaxy.

A. Quasars emit radiation throughout the electromagnetic spectrum from very small volumes, as would be the case for gas spiraling into a black hole.

B. More nearby examples, called *active galaxies*, also show evidence for accretion of matter by a supermassive black hole.

1. Emission lines from the nucleus are broad, suggesting rapid motions induced by the black hole.
2. Large amounts of ultraviolet light and X-rays are emitted from the nucleus.

C. Normal galaxies are also active in some cases, but not obviously so because we view them from the wrong direction.

1. The black hole and the rapidly moving clouds of gas are blocked along our line of sight by a thick torus.

2. Regions within the galaxy aligned along the axis of the torus are exposed to high-energy radiation and, hence, glow.

D. The inner regions of the torus can have a narrow nozzle that helps channel particles into a relativistic jet.

1. The jet formation mechanism may be somewhat similar to that in a gamma-ray burst, with strong magnetic fields involved.
2. We see such jets shooting out from some galactic nuclei, including objects in which the motions of stars indicate the presence of a supermassive black hole.
3. Only one of the two oppositely directed jets is visible in many cases. The side coming toward us looks very bright, and the side going away from us gets diminished in brightness.

E. The spin of a supermassive black hole in one active galaxy (MCG 6-30-15) may have recently been detected.

1. Extra energy is being emitted from the vicinity of the black hole, by matter in the accretion disk.
2. The energy probably comes from the spin of the black hole, which is being tapped by the disk.

V. Interactions among galaxies can rejuvenate a supermassive black hole that had used up material in its vicinity.

A. Material is channeled toward the black hole by the gravitational interaction or merging of the two galaxies.

1. A new accretion disk is formed, and it can feed the black hole.
2. The quasar shines again, as long as it is gobbling up gas.
3. Thus, when quasars first formed, they shined brightly as they accreted the surrounding gas—but as they aged and used up their supply of gas, they faded and became more normal galaxies.
4. If the supply of gas is replenished by an interaction with another galaxy, the quasar is rejuvenated.
5. Indeed, images of most relatively close quasars show that they are interacting or have recently interacted with another galaxy.

B. We have examples of this process occurring in some very nearby galaxies, which can be studied in detail.

C. Each of the galaxies that interact and merge may have a supermassive black hole in its center.

1. One of the most interesting Chandra results is the discovery of two black holes in the merging galaxy system called NGC 6240. For many years, it was not known which of the two galaxies was the active one, but both are!
2. Within a billion years, the two galaxies will have completely merged, and the two black holes will become a single, even more massive black hole.

3. If we are around when the black holes merge, we might detect gravitational radiation emitted during the process—a clear prediction of Einstein's general theory of relativity, to be discussed in Lecture Nine.

D. Many supermassive black holes and galaxies probably grew to their present sizes by the process of merging. Our own Milky Way galaxy is likely to have grown from previous episodes of merging.

Essential Reading:

Ferguson, *Prisons of Light: Black Holes*.

Pasachoff and Filippenko, *The Cosmos: Astronomy in the New Millennium*, 2nd ed.

Supplementary Reading:

Begelman and Rees, *Gravity's Fatal Attraction: Black Holes in the Universe*.

Thorne, *Black Holes and Time Warps: Einstein's Outrageous Legacy*.

Questions to Consider:

1. Given that objects can fall into a black hole, what do we mean when we say that the interior of a black hole is cut off from the Universe?
2. What do you think would happen to Earth's orbit if the Sun were to suddenly turn into a black hole having the same mass? (Remember that the Earth is very far from the Sun, and a black hole having the Sun's mass is much smaller than the Sun.)

Glossary

absorption line: A wavelength (or small range of wavelengths) at which the brightness of a spectrum is less than it is at neighboring wavelengths.

accelerating universe: The model of the Universe based on recent observations that the expansion is speeding up with time.

accretion: The transfer of matter to the surface of a star or a black hole. When the transferred matter goes into orbit around the object, an *accretion disk* is formed.

active galaxy: A galaxy whose nucleus emits large quantities of electromagnetic radiation that does not appear to be produced by stars.

adaptive optics: Optical systems providing rapid corrections to counteract atmospheric blurring.

Ångstrom (Å): A unit of length commonly used for visible wavelengths of light; 1 Å = 10^{-8} cm.

angular momentum: A measure of the amount of spin of an object; dependent on the object's rotation rate, mass, and mass distribution.

anthropic principle: The idea that given that we exist, the Universe must have certain properties or it would not have evolved so that life formed and humans evolved.

antiparticle: A particle whose charge (if not neutral) and certain other properties are opposite those of a corresponding particle of the same mass. An encounter between a particle and its antiparticle results in mutual annihilation and the production of high-energy photons.

apparent brightness: The amount of energy received from an object per second, per square cm of collecting area. It is related to luminosity and distance through the equation $b = L/(4\pi d^2)$.

asteroid: chunk of rock, smaller than a planet, that generally orbits the Sun between Mars and Jupiter.

astronomical unit (A.U.): The average distance between the Sun and the Earth (1.5×10^8 km).

aurora: The northern or southern lights, caused by energetic particles interacting with atoms and ions in Earth's upper atmosphere, making them glow.

Big Bang: The birth of the Universe in a very hot, dense state 13.7 billion years ago, followed by the expansion of space.

binary star: Two stars gravitationally bound to (and orbiting) each other

bipolar outflow: A phenomenon in which streams of matter are ejected from the poles of a rotating object.

black hole: A region of space-time in which the gravitational field is so strong that nothing, not even light, can escape. Predicted by Einstein's general theory of relativity.

brown dwarf: A gravitationally bound object that is insufficiently massive to be a star but too massive for a planet. Generally, the mass range is taken to be 13–70 (or 75) Jupiter masses.

celestial sphere: The enormous sphere, centered on the Earth, to which the stars appear to be fixed.

centrifugal force: The outward force felt by an object in a rotating frame of reference.

Cepheid: A type of pulsating star that varies in brightness with a period of 1 to 100 days.

Chandrasekhar limit: The maximum stable mass of a white dwarf or the iron core of a massive star, above which degeneracy pressure is unable to provide sufficient support; about 1.4 solar masses.

closed universe: A universe having finite volume.

cold dark matter: Nonluminous matter that moves slowly, such as neutron stars and exotic particles.

comet: An interplanetary chunk of ice and rock, often in a very elongated orbit, that produces a diffuse patch of light in the sky when relatively near the Sun as a result of evaporation of the ice.

constellation: One of 88 regions into which the celestial sphere is divided. The pattern of bright stars within a constellation is often named in honor of a god, person, or animal.

corona: The very hot, tenuous, outermost region of the Sun, seen during a total solar eclipse.

cosmic microwave background radiation: Radio electromagnetic radiation that was produced in the hot Big Bang. It now corresponds to $T \approx 3$ K because of the expansion and cooling of the Universe.

cosmic rays: High-energy protons and other charged particles, probably formed by supernovae and other violent processes.

cosmological constant: In Einstein's general theory of relativity, a term (Λ) that produces an acceleration of the Universe's expansion.

cosmology: The study of the overall structure and evolution of the Universe.

crepuscular rays: Beams of light shining through gaps in clouds, usually best seen near sunset or sunrise.

critical density: The average density of the Universe if it were poised exactly between eternal expansion and ultimate collapse, if the cosmological constant is zero.

dark energy: Energy with negative pressure, causing the expansion of the Universe to accelerate.

dark matter: Invisible matter that dominates the mass of the Universe.

degenerate gas: A peculiar state of matter at high densities in which, according to the laws of quantum physics, the particles move very rapidly in well-defined energy levels and exert tremendous pressure.

deuterium: An isotope of hydrogen that contains one proton and one neutron.

deuteron: A deuterium nucleus.

diffraction: A phenomenon affecting light as it passes any obstacle, spreading it out.

Doppler shift: The change in wavelength or frequency produced when a source of waves and the observer move relative to each other. Blueshifts (to shorter wavelengths) and redshifts (to longer wavelengths) are associated with approach and recession, respectively.

$E = mc^2$: Einstein's famous formula for the equivalence of mass and energy.

earthshine: sunlight illuminating the Moon after having been reflected by the Earth.

eccentric: Deviating from a circle. *Eccentricity* is a measure of this.

eclipse: The passage of one celestial body into the shadow of another or the obscuration of one celestial body by another body passing in front of it.

ecliptic: The path followed by the Sun across the celestial sphere in the course of a year.

electromagnetic force: One of the four fundamental forces of nature; it holds electrons in atoms.

electromagnetic radiation: Self-propagating, oscillating electric and magnetic fields. From shortest to longest wavelengths: gamma rays, X-rays, ultraviolet, optical (visible), infrared, and radio.

electron: Low-mass, negatively charged fundamental particle that normally "orbits" an atomic nucleus.

electroweak force: The unification of the electromagnetic and weak nuclear forces.

ellipse: A set of points (curve) such that the sum of the distances to two given points (foci) is constant.

emission line: A wavelength (or small range of wavelengths) at which the brightness of a spectrum is more than it is at neighboring wavelengths.

escape velocity: The minimum speed an object must have to escape the gravitational pull of another object.

event horizon: The boundary of a black hole from within which nothing can escape.

extrasolar planet: A planet orbiting a star other than the Sun; an *exoplanet*.

eyepiece: The small combination of lenses at the eye end of a telescope, used to examine the image.

flat (critical) universe: A universe in which the laws of Euclidean geometry hold.

fusion: The formation of heavier nuclei from lighter nuclei.

galactic cannibalism: The swallowing of one galaxy by another.

galaxy: A large (typically 5000 to 200,000 light years in diameter), gravitationally bound system of hundreds of millions (and up to a trillion) stars.

Galilean satellites: The four large moons of Jupiter (Io, Europa, Ganymede, Callisto).

gamma rays: Electromagnetic radiation with wavelengths shorter than about 0.1 Å.

gamma-ray burst (GRB): A brief burst of gamma rays in the sky, now known to generally come from exceedingly powerful, distant objects.

general theory of relativity: Einstein's comprehensive theory of mass (energy), space, and time; it states that mass produces a curvature of space-time that we associate with the force of gravity.

globular cluster: A bound, dense, spherically symmetric collection of stars formed at the same time.

grand unified theory (GUT): A theory that unifies the strong nuclear ("color") and electroweak forces into a single interaction.

gravitational lens: In the gravitational lens phenomenon, a massive body changes the path of light passing near it so as to make a distorted image of the object.

gravitational redshift: A redshift of light caused by the presence of mass.

gravitational waves (gravity waves): Waves thought to be a consequence of changing distributions of mass.

gravity: The weakest of nature's fundamental forces but the dominant force over large distances because it is cumulative; all matter and energy contribute, regardless of charge.

green flash: A faint green glow sometimes visible in very clear skies just as the last part of the Sun is setting (or the first part is rising).

greenhouse effect: The effect by which the atmosphere of a planet heats up above its normal equilibrium temperature because it absorbs infrared radiation from the surface of the planet.

halo (galactic): The region that extends far above and below the plane of the galaxy.

halo (solar or lunar): A circle of light around the Sun or Moon, having a radius of about 22 degrees, formed by light going through hexagonal ice crystals.

Heisenberg's Uncertainty Principle: One form: In any measurement, the product of the uncertainties of energy and time is greater than or equal to Planck's constant divided by 2π.

homogeneous: The same (density, temperature, and so on) at all locations.

hot dark matter: Nonluminous matter with large speeds, such as neutrinos.

Hubble's law: The linear relation between the distance and recession speed of a distant object: $v = H_0 d$. The constant of proportionality, H_0, is called Hubble's constant.

infinity: All numbers. A countable infinity can be put in one-to-one correspondence with the counting numbers, whereas an uncountable infinity cannot.

inflationary universe: A modification of the standard Big Bang theory. Very early in its history (e.g., $t \approx 10^{-37}$ seconds), when the Universe was exceedingly small, it began a period of rapidly accelerating expansion, making its final size truly enormous. Subsequently, the regular Big Bang expansion ensued.

interference: The property of radiation, explainable by the wave theory, in which waves in phase can add (constructive interference) and waves out of phase can subtract (destructive interference).

interferometer: Two or more telescopes used together to produce high-resolution images.

interstellar medium: The space between the stars, filled to some extent with gas and dust.

inverse-square law: Decreasing with the square of increasing distance.

ionized: Having lost at least one electron. Atoms become ionized primarily by the absorption of energetic photons and by collisions with other particles.

isotopes: Atomic nuclei having the same number of protons but different numbers of neutrons.

isotropic: The same in all directions (that is, no preferred alignment).

Kelvin: The size of 1 degree on the Kelvin (*absolute*) temperature scale, in which absolute zero is 0 K, water freezes at 273 K, and water boils at 373 K. To convert from the Kelvin scale to the Celsius (centigrade, C) scale, subtract 273 from the Kelvin scale value. Degrees Fahrenheit (F) = (9/5)C + 32.

Kepler's third law: If one object orbits another, the square of its period of revolution is proportional to the cube of the major (long) axis of the elliptical orbit.

Kuiper Belt: A reservoir of perhaps millions of solar-system objects, orbiting the Sun generally outside the orbit of Neptune. Pluto is the largest known Kuiper Belt Object.

Large Magellanic Cloud: A dwarf companion galaxy of our Milky Way galaxy, about 170,000 light years away; best seen from Earth's southern hemisphere.

large-scale structure: The network of clusters, voids, and other shapes seen on the largest scales of the Universe.

light curve: A plot of an object's brightness as a function of time.

light year: The distance light travels through a vacuum in 1 year; about 10 trillion km.

lighthouse model: The explanation of a pulsar as a spinning neutron star whose beam we see as it comes around.

Local Group: The roughly two dozen galaxies, including the Milky Way, that form a small cluster.

lookback time: The duration over which light from an object has been traveling to reach us.

luminosity: Power; the total energy emitted by an object per unit time.

MACHOs: Massive compact halo objects—brown dwarfs, white dwarfs, and similar objects that could account for some of the dark matter.

magnitude: A logarithmic measure of apparent brightness; a difference of 5 magnitudes corresponds to a brightness ratio of 100. Typical very bright stars have mag 1; the faintest naked-eye stars have mag 6.

main sequence: The phase of stellar evolution, lasting about 90% of a star's life, during which the star fuses hydrogen to helium in its core.

merging: The interaction of two galaxies in space with a single galaxy as a result.

meteor: The streak of light in the sky produced when an interplanetary rock enters Earth's atmosphere and burns up as a result of friction. If the rock reaches Earth's surface, it is called a meteorite.

meteoroid: An interplanetary rock that is not in the asteroid belt.

Milky Way: The band of light across the sky from the stars and gas in the plane of the Milky Way galaxy (our galaxy).

minor planets: Asteroids. Some astronomers now reserve this term for the largest asteroids and Kuiper Belt Objects.

mirage: An image of an object, usually inverted, formed by light passing through layers of air having different temperatures.

multiverse: The set of parallel universes that may exist, with our observable Universe as only one part.

nebula: A region containing an above-average density of interstellar gas and dust.

neutrino: A nearly massless, uncharged fundamental particle that interacts exceedingly weakly with matter. There are three types: electron, muon, and tau neutrinos.

neutron: Massive, uncharged particle that is normally part of an atomic nucleus.

neutron star: The compact endpoint in stellar evolution in which typically 1.4 solar masses of material is compressed into a small (diameter = 20–30 km) sphere supported by neutron degeneracy pressure.

nuclear fusion: Reactions in which low-mass atomic nuclei combine to form a more massive nucleus.

nucleosynthesis: The creation of elements through nuclear reactions, generally nuclear fusion.

open universe: A universe whose volume is infinite.

parsec: A unit of distance equal to 3.26 light years (3.086×10^{13} km).

particle physics: The study of the elementary constituents of nature.

phase transition: The transformation of matter from one phase (e.g., liquid) to another (e.g., solid).

photon: A quantum, or package, of electromagnetic radiation that travels at the speed of light. From highest to lowest energies: gamma rays, X-rays, ultraviolet, optical (visible), infrared, and radio.

photosphere: The visible surface of the Sun (or another star) from which light escapes into space.

pinhole camera: A hole in an opaque sheet used to project an image of the Sun.

Planck's constant: The fundamental constant of quantum physics, *h*; a very small quantity.

planet: An object of substantial size (diameter > 1000 km) that orbits a star, but not massive enough for nuclear fusion ever to begin. An upper limit of about 13 Jupiter masses is generally adopted.

planetary nebula: A shell of gas, expelled by a red giant star near the end of its life (but before the white dwarf stage), that glows because it is ionized by ultraviolet radiation from the star's remaining core.

planetary system: A collection of planets and smaller bodies orbiting a star (e.g., our Solar System).

planetesimals: Small bodies, such as meteoroids and comets, into which the solar nebula condensed and from which the planets subsequently formed.

pole star: A star approximately at a celestial pole (Polaris, in the north).

positron: The antiparticle of an electron.

progenitor: In the case of a supernova, the star that will eventually explode.

prograde motion: The apparent motion of the planets when they appear to gradually move from west to east among the stars; *retrograde motion* is the opposite direction.

proton: Massive, positively charged particle that is normally part of an atomic nucleus. The number of protons in the nucleus determines the chemical element.

proton-proton chain: A set of nuclear reactions by which four hydrogen nuclei (protons) combine to form one helium nucleus, with a resulting release of energy.

protostar: A star still in the process of forming, embedded in a thick collapsing envelope of gas and dust.

pulsar: An astronomical object detected through pulses of radiation (usually radio waves) having a short, extremely well-defined period; thought to be a rotating neutron star with a very strong magnetic field.

quantum fluctuations: The spontaneous (but short-lived) quantum creation of particles out of nothing.

quantum mechanics: A 20th-century theory that successfully describes the behavior of matter on very small scales (such as atoms) and radiation.

quasar (QSO): A star-like, extremely luminous object, typically billions of light years away. Now thought to be the nucleus of a galaxy with a supermassive black hole that is accreting matter from its vicinity.

quintessence: A new particle or field in physics that can lead to repulsive dark energy.

radial velocity: The speed of an object along the line of sight to the observer.

red giant: The evolutionary phase following the main sequence of a relatively low-mass star, such as the Sun; the star grows in size and luminosity but has a cooler surface.

redshift: Defined to be $z = (\lambda - \lambda_0)/\lambda_0$, where λ_0 is the rest wavelength of a given spectral line and λ is its (longer) observed wavelength. The wavelength shift may be caused by recession of the source from the observer, or to the propagation of light out of a gravitational field.

refraction: The bending of light as it passes from one medium to another having different properties.

relativistic: Having a speed that is such a large fraction of the speed of light that the special theory of relativity must be applied.

resolution: The clarity of detail produced by a given optical system (such as a telescope).

rest mass: The mass of an object that is at rest with respect to the observer. The effective mass increases with speed.

rest wavelength: The wavelength radiation would have if its emitter were not moving with respect to the observer.

rotation curve: A graph of the speed of rotation vs. distance from the center of a rotating object, such as a galaxy.

Schwarzschild radius: The radius to which a given mass must be compressed to form a nonrotating black hole. Also, the radius of the event horizon of a nonrotating black hole.

singularity: A mathematical point of zero volume associated with infinite values for physical parameters, such as density.

solar mass: The mass of the Sun, 1.99×10^{33} grams, about 330,000 times the mass of the Earth.

space-time: The four-dimensional fabric of the Universe whose points are events having specific locations in space (three dimensions) and time (one dimension).

special theory of relativity: Einstein's 1905 theory of relative motion; gravity excluded.

spectrum: A plot of the brightness of electromagnetic radiation from an object as a function of wavelength or frequency.

star cluster: A gravitationally bound group of stars that formed from the same nebula.

string (superstring) theory: A possible unification of quantum theory and general relativity in which fundamental particles are different vibration modes of a tiny, one-dimensional "string" instead of being localized at single points.

strong nuclear force: The strongest force, it binds protons and neutrons together in a nucleus. Actually, it is the residue of the even stronger *color force* that binds quarks together in a proton or neutron.

sun dog: A pair of bright spots on, or just outside, the location of the solar halo at the Sun's altitude above the horizon.

sun pillar: A faint pillar of light above the Sun in the sky, best visible after sunset.

supercooled: The condition in which a substance is cooled below the point at which it would normally make a phase change.

supergiant: The evolutionary phase following the main sequence of a massive star; the star becomes more luminous and larger. If its size increases by a very large factor, it becomes cool (red).

supernova: The violent explosion of a star at the end of its life. Hydrogen is present or absent in the spectra of Type II or Type I supernovae, respectively.

supernova remnant: The cloud of chemically enriched gases ejected into space by a supernova.

symmetric: Forces that are symmetric act identically. They act differently when the symmetry is broken.

terrestrial planets: Rocky, Earth-like planets. In our Solar System: Mercury, Venus, Earth, Mars.

tidal force: The difference between the gravitational force exerted by one body on the near and far sides of another body.

time dilation: According to relativity theory, the slowing of time perceived by an observer watching another object moving rapidly or located in a strong gravitational field.

transverse velocity: The speed of an object across the plane of the sky (perpendicular to the line of sight).

Universe: All that there is within the space and time dimensions accessible to us, as well as regions beyond (but still physically connected to) those that we can see.

variable star: A star whose apparent brightness changes with time.

virtual particle: A particle that flits into existence out of nothing and, shortly thereafter, disappears again.

weak nuclear force: Governs the decay of a neutron into a proton, electron, and antineutrino.

white dwarf: The evolutionary endpoint of stars that have initial mass less than about 8 solar masses. All that remains is the degenerate core of He or C-O (in some cases O–Ne–Mg).

wormhole: A connection between two universes or different parts of our Universe. Also: Einstein-Rosen bridge.